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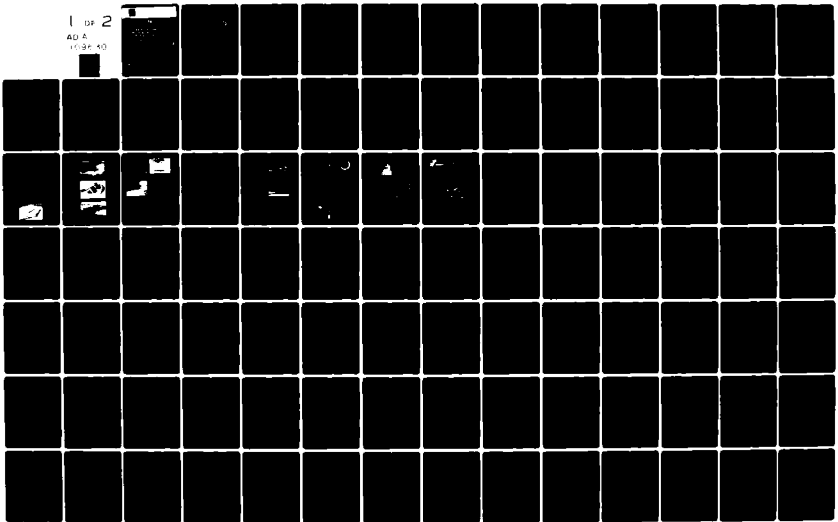

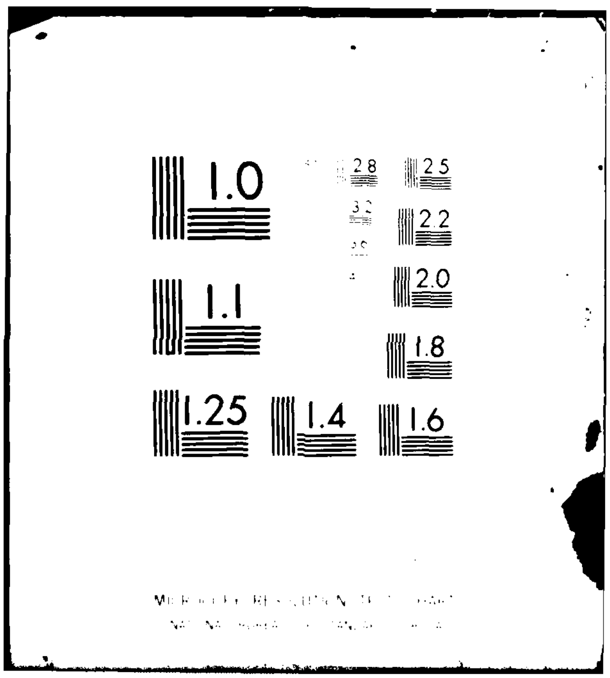
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Problems and Opportunities in the Design of Entrances to Ports and Harbors

Proceedings of a Symposium

August 13-15, 1980
Fort Belvoir, Virginia

Panel on Harbor/Port Entrance Design

Marine Board

Assembly of Engineering

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THE DESIGN OF ENTRANCES TO PORTS AND HARBORS

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Convened by the Panel on Harbor/Port Entrance Design
for the
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National Research Council

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A

PANEL ON HARBOR/PORT ENTRANCE DESIGN

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FOREWORD

Ben C. Gerwick
Chairman, Marine Board

Harbors offer vessels some measure of protection from the natural forces of winds, waves, and currents and a bottom capable of holding them at anchor. Of inestimable importance in the history of the world, natural harbors have been a necessary condition of seagoing trade and warfare. With trade and travel, harbors become ports--gateways of goods and people at the juncture of land and sea trade routes.

The technology of harbors and ports has a long history. The Phoenicians built harbors at Sidon and Tyre on the Mediterranean as far back as the thirteenth century B.C. A deepwater pier was constructed at Alexandria in 332 B.C., and the Pharos lighthouse, completed in 280 B.C., has been known as one of the Seven Wonders of the ancient world. The purpose and social importance of ports and harbors have not changed; present technologies serve many of the same purposes as those of ancient times--safe navigation, a protected haven, and the ability to load and unload passengers and cargoes. What has changed are the size and nature of the world cargo fleet and the socioeconomic concerns of populations.

There is increasing demand abroad for this country's coal and food, for example, and increasing domestic demand for imported oil. The ships necessary to profitable trade in this international traffic demand deeper drafts and more room to stop: they present far different characteristics of maneuverability than the ships America's ports were designed to receive. While it was always necessary to know the patterns of tides and currents, the location of hazards, and other facts about the physical environment of ports and harbors, it is now necessary to know much more to design port and harbor works, manage greatly increased traffic, and effect safe passage.

Commercial ports create wealth and attract settlement. In the past fifteen years, increasing attention has been directed to the social costs of settlement and trade on the world's coasts--to the effects of wastes emptied into waterways and the oceans, and to the potential for oil pollution and accidents involving hazardous cargoes. Concern for the marine and coastal environment brought about landmark legislation in the United States in the past decade, and created new decision making entities and procedures.

The Marine Board has been concerned for some time that the rapid changes in naval technologies and social patterns, and the intensi-

fication of discernible trends affecting the design of ports and harbors have not been met with corresponding alacrity and intensification of efforts to gather crucial data, formulate needed analytical techniques, or develop the processes for synthesis of all significant factors in a rational set of procedures for design. This situation can be seen in sharp focus at the entrance to a port or harbor, a critical area for navigation and traffic control that most clearly manifests the complex interactions of physical forces, vessel traffic, and other factors with the results of the designer's work. This area also seems a convenient locus for investigating the engineering implications of designing ports and harbors to meet several objectives; among them, safety of the public, of navigation, and of the marine environment, increased economic activity, and accommodation of the vessels of today and tomorrow.

Among the responsibilities of the Marine Board under its charter is to undertake, on its own initiative, investigation of issues that lie outside the compass of any single agency of government. Accordingly, the National Research Council appointed a panel at the request of the Marine Board to investigate problems and opportunities in the design of entrances to ports and harbors under the board's direction. The panel planned and convened an interdisciplinary meeting of about 50 experts in the summer of 1980 to exchange information on these problems and opportunities, and to identify the most pressing problems requiring solution.

The participants represented a great many views and interests in ports and harbors--those of research and design engineers, marine scientists and environmentalists, naval architects, port directors, dredgers, ship operators and captains, harbor pilots, salvors, authorities on modeling and simulation, representatives of the U. S. Coast Guard, U. S. Army Corps of Engineers, National Oceanic and Atmospheric Administration, and the U. S. Navy. An interesting result of bringing together such distinctly different views and interests was the enthusiastic exchange of information and experience and the questions and answers of the participants that gave ample evidence of the need most often expressed in the meeting: the need for methods of analysis and decision making that encompass necessary engineering and functional information, that allow full consideration of fundamentally different concerns and that instantiate man's long experience with ports and harbors.

SUMMARY

The most critical area of a port or harbor for navigation, maintenance, and potential effects on the physical and biological marine environment is the entrance. The entrance to a harbor or port might conveniently be described as that region of a ship channel between the open sea and the protected area of the harbor, including, on the seaward side, the nearby approach fairways, and on the harbor side, sufficient distance to permit a ship to stop.

A number of considerations affect the design of this critical area: the controllability of ships, transport and deposition of sediments, patterns and strength of waves, tides, and currents, interactions of ship traffic, environmental effects of structures and dredging operations, and others. Yet the development, testing, and improvement of reliable predictive models and development of a systems approach to the planning of these critical areas have not kept pace with the challenging demands of existing and projected needs for harbors and ports. Detailed attention is given to these subjects and their implications in the formal presentations collected in ~~succeeding~~ sections ~~of~~ these proceedings.

In iterative and collaborative workshop sessions (described under "Workshops," page 157), participants in the meeting agreed that the most important problems requiring resolution in the design of entrances to ports and harbors are the following, in order of urgency and consequence:

- Improved and validated models for the prediction of horizontal and vertical ship movements in the particular conditions of harbor entrances;
- Use of systems analysis in the design of harbor entrances;
- Reliable and economical measurement, reduction, presentation, and storage of environmental data;
- Cost-effective models of the physical environment for prediction of natural conditions and forces, and changes caused by human activity;
- Improved procedures for prediction of shoaling rates and patterns, including development and verification of appropriate field methodologies;
- Improved entrance-channel design and operating criteria;

- Development of accepted standards and uniform methods for measuring and assessing navigability of harbor entrances;
- Quantitative definition of the needs of mariners;
- Review and reform of decision making processes for port and harbor projects, and
- Evaluation of the importance of natural resources for balanced decisions about harbor siting and related matters, and increased attention to the restoration of natural habitats.

CONTENTS

INTRODUCTION

Robert L. Wiegel
Chairman
Panel on Harbor/Port Entrance Design

Throughout history, engineers have been concerned with ships, ports, aids to navigation, land reclamation, the protection of coasts from erosion, and the design of structures to withstand the great forces of the ocean during storms at sea. Engineering works are not constructed as an end in themselves. They are made for the economic and other social benefits of people, for military reasons, or for both. Thus, the conception, planning, design, construction, and operation of these works, and the development and management of the systems of which they are a part, have always been carried out in concert with broader plans. The significance of harbors, therefore, is a distinctive element woven into the culture and politics of peoples and nations.[1] This has been so since the time of the Minoan civilization of remote antiquity.[2/3] Owing to the extensive use of shipping and harbors for more than 5000 years, it is evident that harbors have been, and still are, a major factor in the development of civilization. Harbors, ports, and ships are essential to the movement of ideas, techniques, and goods from one place to another.

What is a port, and what is a harbor? Many times the words are used interchangeably, as ports are often constructed within harbors. A study of the definitions of these words, together with words of similar roots, indicates that a port is a place where cargoes are loaded or unloaded, and a harbor is a place that provides shelter and anchorage for ships. There are ports that are not sheltered and harbors that have no ports. This workshop will be concerned with harbors, and will not touch upon the problems of offshore terminals that are not sheltered. Much of the development of offshore terminals has been brought about by the deep drafts of the very large ships used in the bulk cargo trade. The cost of dredging deep channels and other restraints against traditional harbors are such that offshore terminals sometimes offer a better solution. In some regions, it is relatively easy to have deepwater ports.[4]

There are six major types of natural harbors: a well-protected bay, the lee of an isle (today, perhaps man-made) or a rock connected to shore by a tombolo, the lee of a reef, the portion of an open bay that is reasonably well sheltered from the prevailing waves by refraction, just upstream from a river mouth, and in the broadest sense

of a "harbor," the beaching of a craft. There are, of course, variations of these.

Naturally occurring well-protected harbors are not common, but those that exist, such as Sydney, Australia, are well known. The Phoenicians made use of the lee of small isles just offshore, such as Tipasa, adding moles for additional protection and cargo handling. Port Moresby, Papua New Guinea, is an example of a harbor sheltered by an extensive reef. There are many examples of open roadsteads that are reasonably sheltered from prevailing waves, such as Santa Cruz, California, located on Monterey Bay. The degree of shelter depends on the characteristics of the ships. Thus, many of the large bulk cargo ships in operation today, especially tankers, can load and unload in what might be heavy seas for smaller ships. River mouths have been used and are being used in many parts of the world, not only for the shelter they afford but because the river is a waterway to the hinterland. The Rhine River is a classic example. Beaching is still used in many parts of the world, often for small fishing vessels, owing to the lack of natural harbors and the relatively high cost of artificial harbors.

One of the most important and difficult parts of a harbor is the entrance. Many harbor entrances have been found to be difficult for ships to navigate owing to currents, bars, and waves. These problems are not new. The early sixteenth-century sailing directions of Pierre Garcie contain the following warning:[5]

> Know that when the sea breaks more than two rollers on the Plateau de St. Jean de Lux (in the Bay of Biscay) you must not attempt to enter LeBoucaut; take heed indeed, because it's not worth it. But if the seas are not breaking you can go in safely.

The entrances of harbors that once had high traffic volume have closed completely. A case history of the closure of such a natural entrance, and its eventual reopening and maintenance is useful to engineers. Such a case, with information dating back to the tenth century A.D., is that of Aveiro, Portugal.[6]

Better dredges, navigation aids (buoys, lights, radar, loran), and ship handling now make it possible to improve our harbor entrances. With these improvements, the use of local pilots, and the development of marine traffic control systems, we can now make better use of the entrances. Nevertheless, we are all aware of a number of instances in recent years in which ships have run aground and foundered at a harbor entrance.

Several programs are being developed and tested for better control of marine traffic in harbors and in the sealanes near the harbors. These developments are of great importance to high-density shipping harbors, and effecting them successfully is a major challenge. They must be coupled with improvements in the maneuverability of ships and barges in restricted waterways, improvements that demand greater ability to analyze the motion of ships in these conditions.

In contrast to the high-density harbors employing advanced technology are those of such low density and economic activity that little can be done. One common type is the harbor just inside the mouth of a river. The successful use of such harbors often requires the design and use of special types of small ships that can "ground" on bars without much damage. A major challenge to the engineer is the development of inexpensive and reliable navigation aids for the entrance and passages of these natural harbors.

To do their jobs properly, engineers need to be able to predict reliably the quantitative as well as the qualitative effects of the system consisting of a harbor layout, its structural appurtenances, and the ships that use it. As an example of the type of problem that still exists, consider model studies of sedimentation at harbor entrances. Many studies have been made, and many ideas have been tried to solve the problem of making quantitative predictions (including the time-rate) of what will happen to sediments at and near a natural, man-modified, or artificial entrance to a harbor. The problem is difficult when only waves and tidal flows are considered. In a recent paper, Kamphuis concludes for hydraulic models:[7]

> After a number of years of study, coastal mobile bed models are classified and scale effects resulting from various non-similarities are discussed. Two methods of classification are given--one according to non-similarity of basic scaling relationships and another according to the type of model required. All but one class of model is subject to substantial scale effect and thus no easy scaling recipes can be given. Modelling still remains an art and this extensive study only results in pointing out some common pitfalls to be avoided. Models using lightweight material are shown to be eminently unsuitable for inshore areas and it appears to be virtually impossible to determine time scales for bed morphology because of scale effect. The simple tracer model appears to yield best value for money invested.

When harbors are located in estuaries, density flows exist and the rivers usually transport sediment into the harbor. The problems are much more complex than for the "simple" case considered above.

The development of reliable tools to analyze the interaction of ships, waves, tides, currents, river flows, and sediments, together with the effects of structures and dredging operations (including dredged sediment disposal) from the standpoint of harbor design and ship operation is a very challenging problem for us today.[8]

In addition to the natural harbors, man has constructed artificial harbors, components of natural harbors, and improvements. Some of the problems of entrances of both natural and artificial harbors will be considered at this meeting.

Purpose and Objectives of Meeting

The subject of this three-day meeting is the design of harbor/port entrances for safe, efficient use. The harbors and ports to be considered are those used by ships engaged in international or intracoastal trade (or both). The objective of the workshop is to identify the principal problem areas, to assess the state of our knowledge, and to recommend the research needed to transform the nearly empirical approach used today to a completely rational design procedure for entrances to ports and harbors.

A completely rational procedure would consider the requirements of the following five functions: the economic vitality of the United States, the needs of the users, harbor/port operations, ship operations, and the environment.

Definition of Harbor/Port Entrance

Basic procedural rules for this meeting were formulated by the panel. First is a narrow definition of harbor/port entrance. The panel decided that for the purpose of this workshop the entrance of the harbor/port is that region of the ship channel between the open sea (or large lake) and the protected region of the harbor. On the seaward side, it includes the nearby approach fairways, and on the harbor side, sufficient distance to permit a ship to stop. Seaward of the "entrance" there is essentially unlimited space and water depth from the standpoint of ship traffic. Shoreward of the "entrance," the space and depth are generally greatly restricted. The panel decided that a more detailed definition would not allow the flexibility needed to consider many different harbor and port types.

Presentations

The formal presentations to follow this introduction and the keynote address on harbors and ports are grouped in three areas of concern: those pertinent to the design and maintenance of harbor/port entrances, those of the ships and users, and those of nature and the environment. The subjects to be considered in each area of concern are: in Design and Maintenance, the principal considerations for design, rules and regulations governing entrances, and aids to navigation; in Concerns of Ships and Users, shipboard aids to navigation and channel width, ship controllability, and other concerns of ship operators and pilots; in Nature and Environment, sedimentation, tidal hydraulics, waves, and the effects of ports and harbors on the environment.

Identification of Problems

The workshops, using an interdisciplinary approach, address three broad technical areas: harbor/port entrance hydraulics, ship/harbor interaction, and sediment transport-deposition/scour. Each of these areas requires detailed consideration of a number of technical subjects, listed below. (Those common to more than one broad area are marked by an asterisk.)

Harbor/Port Entrance Hydraulics

- Fluid hydrodynamics
- Wave climate (including shallow-water directional spectra)
- Hurricanes
- Hydraulic models
- Harbor surging
- Entrance structures*
- Coastal zone management*
- Data acquisition*
- Environmental effects*

Ship/Harbor Interaction

- Ship hydrodynamics
- Navigation aids (including real-time environmental data)
- Pilots
- Tug operators
- Ship control
- Free-running ship model
- Casualty studies
- Salvage (including contingency planning)
- Small boats
- Vessel Traffic Safety Systems (VTS)
- Coastal zone management*
- Port authority
- Environmental effects*
- Propeller wash

Sediment Transport-Deposition/Scour

- Sediment transport-deposition/scour (sand, silt, clay)
- Dredging
- Entrance structures*
- Movable-bed models
- Coastal zone management*
- Data acquisition*
- Environmental effects*
- Fisheries

Workshop participants were encouraged to write short statements of the problems they considered most important in harbor/port entrance

design. These were then studied by the participants, who each listed the ten most important or urgent, in order. After the final tally, small groups assisted rapporteurs in drafting the workshop's statement of each problem and the needed research or action.

These statements were reviewed in plenary session, where additions or minor changes were made where approved by all participants.

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KEYNOTE ADDRESS
THE IMPORTANCE AND ECONOMIC STATUS OF AMERICA'S
PORTS AND HARBORS

Henry E. Soike

Throughout the 200-year history of our nation, seaports have grown and developed into centers of population through marine commerce. Port managers believe that their ports--large or small--are unique major business enterprises, producing significant economic benefits for their communities and providing essential transportation services for world commerce.

The United States' port industry contributes mightily to our national economy as well, and pours billions of dollars into the federal treasury. In 1978, for example, the activities, direct and indirect, of the nation's deep-draft ports supported more than one million jobs producing personal income of $10.6 billion, and adding $32.1 billion to the gross national product. The same year, these ports generated $11.1 billion in federal revenues, including $5.6 billion from customs duties and $12 million from vessel entry fees. By contrast, expenditures by the U. S. Army Corps of Engineers for operation, maintenance, and construction of channels and harbors came to $410.4 million. Adding U. S. Coast Guard expenditures for aids to navigation brings the total to just $690 million. America's ports are a source of considerable profit to the federal government. Moreover, they provide facilities that are readily available for use in times of war and national emergency.

Though the U. S. seaport industry's statistical profile is impressive, its greater significance is represented by the essential nature of its service to the nation's transportation system. The United States leads the nations of the world in volume of exports and imports. It is the world's leading supplier of agricultural commodities and manufactured goods. Growing volumes of raw materials are needed to sustain domestic industrial and agricultural production. In all, the ports of the United States annually handle more than one billion tons of oceanic foreign commerce. No one is predicting anything other than a continuing rise in these volumes.

The development of the United States' port system depends to a great extent on partnership between public port authorities and the federal government. The assumption of this partnership is that the port authorities build shoreside facilities and the related infrastructure, and the federal government assumes primary responsibility for the construction and maintenance of harbors and

navigation channels. The partnership has been very productive, accruing benefits to both parties and resulting in one of the finest port systems in the world.

Recently, however, the federal partner attempted to change the rules. The Carter Administration's water policy reforms, announced in June 1978, call for the states to share the costs of all federal water projects, includir navigation projects. Administration spokesmen said the reform was designed to provide for "meaningful involvement" of states in the selection, development, and operation of federal water resource projects. Each state would be required to finance five percent of the cost of non-vendable inland and deepwater navigation projects. A very rough formula was proposed for apportioning state shares on multistate projects. These proposals were embodied in cost-sharing legislation introduced in the 96th Congress. After hearings in both the House of Representatives and the Senate, no action was taken. The proposals became embroiled in a general water-policy debate and in the Omnibus Water Resources Projects Bill.

Faced with opposition to legislated cost sharing, the Carter Administration tried other approaches. As part of the President's water policy review, 11 criteria were established for decisions on funding of water projects and on their authorization in appropriations bills, including the selection of new planning and construction starts. Criterion 6 states, "Projects will be given expedited consideration where state governments assume a share of costs over the above existing cost sharing." Besides this subtle pressure to expand cost sharing without Congressional approval, the Corps of Engineers recently began to require sponsors to agree in principle to future five percent cost sharing for new or modified navigation projects. Port managers are opposed to the legislative proposals and to pressures to institute cost sharing. Our ports are national assets, and it is only fitting and proper that the federal government continue to bear the full responsibility for navigation projects.

Cost sharing would create inequities. To raise the funds necessary to meet their share of the costs of navigation projects authorized by the Corps of Engineers, states, by necessity, would be forced to draw upon their own tax revenues. Those taxes would fall on the state's own resources. The states cannot recoup these costs from the broad range of port beneficiaries. State taxation of port traffic is effectively precluded by the Constitution, which forbids the levying of imposts or duties on imports or exports without the consent of Congress.

On the other hand, should a state, for whatever reason, be reluctant or unwilling to allocate tax resources to navigation projects, the burden would necessarily fall on the ports themselves. The wealthier ports might well be able to bear it, although port authorities for whom marine operations are marginal or unprofitable might be obligated to draw on revenue generated by other activities, such as airport operations. The result would be to impose an unfair burden on users of airports or whatever is taxed. Ports that lack the financial means of supporting needed navigation improvements would have to do without, thus placing them at a disadvantage to their more affluent rivals. Cost sharing in this instance would have the

obviously discriminatory effect of favoring some ports at the expense of others. Under these circumstances, cost sharing would contravene the long-standing federal policy of neutrality in matters affecting interport competition, and clearly violate the constitutional stricture that, "no preference shall be given by any regulation of commerce or revenue to the ports of one state over another."

Public port authorities in the United States operate very close to the margin. Many barely break even, or fail to cover costs entirely. They, too, are hard pressed by inflation. A recently published report of the National Transportation Policy Study Commission projects that under conditions of medium growth, the capital investment requirements of the ports, harbors, and facilities of the United States serving international marine transportation will total $12.9 billion (in 1975 dollars) between the years 1976 and 2000. Of that sum, $9.4 billion will have to come from state and local governments, including primarily public port authorities and private facility operators. That is the investment that will be required to provide the docks, terminals, and equipment needed to accommodate our international commerce.

Problems in financing facilities and cost sharing are compounded by the intractable delays in granting dredging permits, and by denials of approval for berth maintenance and new port projects. These delays are costly to port interests, shippers, and to foreign trade and national security interests. The effect of dredging delays can be well illustrated by some of the problems confronting coal exports. Over the next 20 years, coal exports from the U. S. are projected by the World Coal Study (WOCOL) to increase from two to six times the 1979 level of 59 million metric tons. But our existing port capacity is insufficient to load that much coal. A particular problem is the draft restrictions at the major coal-loading ports of the United States. Large coal-carrying bulk ships of 100,000 tons or greater, such as those that will enter international coal trade, draw 50 feet or more of water. The present controlling depths at mean low water of the main channel approaches to the major coal ports of Philadelphia, Baltimore, and Norfolk are 40 feet, 42 feet and 45 feet, respectively. Deeper draft vessels, those with greater carrying capacity, must move out at high tide or leave the ports partially loaded.

Shippers confronted by the heavy cost per ton of transporting coal over long distances can be expected to turn to ships that yield maximum economy of scale. As has been borne out by experience in the crude oil trade, the use of very large ships can mean rather substantial savings in transportation costs per ton. A few extra inches in draft can mean the difference of several thousand tons of carrying capacity. Adding a foot or more can make a substantially greater difference. In these circumstances, shippers are bound to employ, where practical, the largest vessel that can be accommodated at the ports where coal is to be delivered.

At least ten ports in Europe and Japan are now capable of receiving coal ships with a maximum capacity of 145,000 DWT or more, vessels far larger than any that can be fully loaded today at the ports of the United States. There are modern loading ports in Australia, Canada, and South Africa, all of which are major coal exporters, capable of

handling vessels in excess of 200,000 DWT. Foreign customers have made it clear that if the draft problem of ports in the United States is not resolved satisfactorily, they will go elsewhere for their coal.

Despite mounting evidence that coal exports could make a very substantial contribution to this country's position in world trade, major port-deepening projects that would directly affect major coal ports, such as Baltimore and Hampton Roads, have been held up by budgetary considerations, problems in securing permits, and prolonged legal proceedings. Ports in the West are now being evaluated for coal export to Pacific Rim nations. The Port of Grays Harbor that I manage has an excellent site that can be developed to handle unit trains from rail carriers that operate from the major coal fields in the West. Nevertheless, after 14 years of effort, we too lack the necessary deeper draft capability. If this nation is to maintain its primacy in international trade, it is essential that port-deepening projects clearly in the national interest should be speedily authorized and completed.

Managers of ports recognize the critical need for adequate navigation facilities to assure safe transit of ships that yield maximum economy of scale. The consideration of adequate harbor and port entrance design by this group is most timely, and can result in improvement to the economic well-being of our nation.

DESIGN AND MAINTENANCE

HARBOR/PORT ENTRANCE DESIGN

Eugene H. Harlow

The design of entrances to ocean harbors, like most design problems in engineering, is an exercise in achieving a compromise among conflicting aims. In the open ocean, a vessel has virtually unlimited space to maneuver. Collision with land is not a hazard, but the ship may be buffeted by waves and swells, shrouded in rains and fog, blown off course by wind, caught in transverse currents or endangered by ice floes or icebergs. Approaching a harbor, all these factors may still be present, but to gain shelter from the hazards of the sea, the vessel now has to follow an accurate route, avoiding collision or grounding on the shores, or on the very breakwaters that provide the shelter.

No two harbors are alike. Each approach pits the skill of the ship captain or pilot against the natural forces that prevail as the vessel moves closer to the obstacles it must at all costs avoid. The contrast between the safety soon to be reached in the harbor and the hazard to the ship's hull in traversing the entrance can hardly be more chilling. The presence of large rocks or irregular masses forming a breakwater -- ideally suited to ripping a jagged gash in a ship-- form a narrow slot through which the vessel must pass in order to reach quiet water and a place to unload its cargo or its passengers. The slot must be narrow in order to exclude wave energy, but it must be wide enough to allow "safe" entry.

"Safe" is a subjective term that depends on judgment. The harbor designer, the port agency, the ship captain, and the pilot may have differing views about the safety of a harbor entrance--views affected by the weather, the alternative harbors that may be available, and the time constraints under which the vessel operates.

To design a harbor entrance, assuming the harbor is not a natural one that needs no man-made props, one must of course consider the types of vessels that will enter or leave it. For example, in the days of sailing vessels, a harbor entrance could not be lined up with a strongly prevalent wind direction, else ships could seldom enter or leave it. Today, the channel dimensions must be large enough to pass the largest ship expected to call at the port, despite the possibility that these dimensions may require a wide opening between breakwaters, admitting more wave energy than desirable or needed for smaller vessels, and despite the sedimentation that may occur at an accelerated rate in the deeper channels needed for the larger ships.

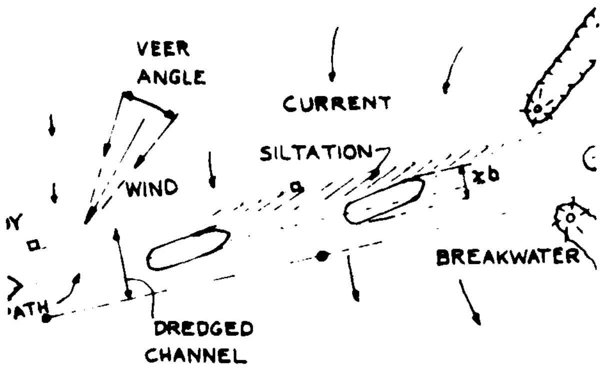

Figure 1. Change of course necessary to steer into current at harbor entrance.

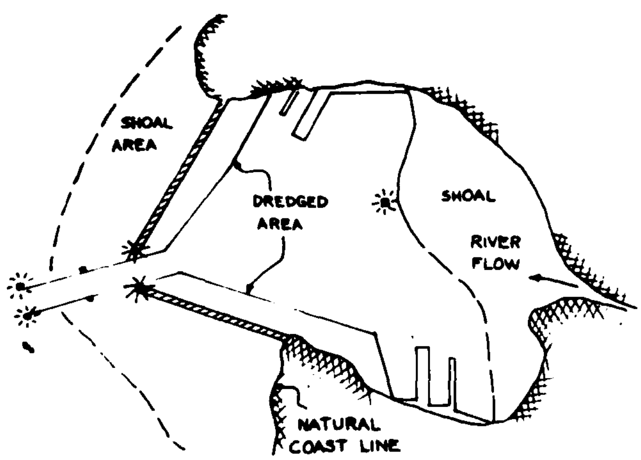

Figure 2. Placement of buoys between those marking changes in direction reduces pilot error.

Navigation in restricted waters remains more an art than a science. As the training of pilots becomes more sophisticated, simulation devices are frequently built to aid in the training process. Yet so far, man's visual perception of movement is the ability upon which we must ultimately rely in steering a vessel and in regulating its propeller speed to accomplish a passage between the obstacles represented by a harbor entrance.

Perception is almost entirely the controlling element in negotiating curves. Even on a straight course, the harbor designer must be aware of the pilot's predicament in countering the varying effects of environmental forces on his vessel.

When entering a harbor under adverse conditions of current and wind, as illustrated in Figure 1, there must be a change in direction or rudder angle to steer a vessel on a straight course.

The ship must be steered at some angle into the current and wind to compensate for a varying lateral force, if it is to remain on a straight course that will maintain adequate clearance between the ends of the harbor breakwaters. The current is likely to be variable, and may be stronger near the ends of the breakwaters than in the sea. The wind direction is not steady, but veers through an angle at irregular intervals. The rudder angle must be increased for stronger current or wind, and decreased for weaker current, or for more favorable direction of either one of them. Steering is easier if the desired path is a straight line and if two or more range markers on shore can be lined up visually along this path. Many recent tracking tests have shown that pilot error in following a channel is reduced considerably if intermediate buoys are placed between those that mark changes in direction, as in Figure 2. This is simply because one's perception of a straight path depends on a reference line that is marked by two or more fixed objects. Rudder angle can then be adjusted to maintain alignment with these fixed objects. On the other hand, with only one object in view, a pilot tends only to steer toward it, relatively unaware of possible side drift. The course is then parabolic rather than straight, the curvature a function of the relative strength of current (or wind) to the ship's forward speed.

Channel design must allow for this kind of deviation, unless a sufficient number and arrangement of channel buoys and range markers are provided to give pilots at least two of them ahead as a reference line at all times.

Because of the steering angle of the vessel as it approaches the harbor entrance, the vessel sweeps across a greater width of channel than its own beam width. The width that is swept can be as much as twice the beam, depending on the ratio of speed to the lateral wind and current.

Once in the harbor, both currents and winds will be reduced, and the vessel will require less steering compensation. On the other hand, decreasing velocity will cause less steering response, so that the ship may tend to move in the direction of its axis, rather than to follow the desired path.

The strong current vectors across the channel may tend to sweep sand and silt into the channel (in the shaded area of Figure 1, for

example). Heavy sedimentation may occur both in the harbor and offshore from the entrance when river flow is strong.

Tidal movements are critical in the transport of sediments, as well as of suspended pollutants.

Long-period waves sometimes create surge and harbor oscillations that not only may be damaging to ship mooring or cargo handling, but may complicate entrance conditions.

Wind set-up, causing surface water to flow in the wind's direction, is frequently the dominant factor causing water movement in both the vertical and horizontal direction.

The variety of design considerations and the consequences of particular design decisions can be seen in existing and proposed examples of ports and harbors. Figure 3, for example, shows a synthetic harbor with a protecting breakwater parallel to the coast. To enter it, a ship must turn outside the roundhead and move along a lee shore before reaching quiet water. The secondary and tertiary breakwaters increase the protection offered smaller vessels.

Figure 4 shows a test harbor used to evaluate how tankers respond to the challenges of maneuvering in current and around bends. Get to the L-head pier, and you win a silver dollar!

The entrance to Manfredonia, illustrated in Figure 5, is a long hockey-stick pier with breakwater. It is apparent in the photograph that entering is easier than turning here. Figure 6 illustrates the harbor of Ashod, Israel, at the east end of the Mediterranean. This harbor has exactly the same shape an an ancient Roman harbor whose remnants were discovered underwater a few miles away after this one was designed. It is interesting that the harbor at Ashod is a good one for sailing vessels.

The synthetic island drawn in Figure 7 would have harbored twin nuclear power plants. Dual entrances are indicated for support vessels. One would nearly always provide entering shelter, and the exit, of course, would always be straight ahead. Figure 8 shows a simple entrance; in this case, to a marina in Ithaca, New York.

Figure 9 indicates how protection for big ships can be achieved behind rocky islands. The design would have been for sea berths, rather than harbors, in this instance. Aristotle Onassis tried to get permission for a terminal in this area--the Isles of Shoals, New Hampshire--to serve a refinery.

In Figure 10, the sea berth built by Burmah Oil behind Grand Bahama Island can be seen. It proved a deep, rough site for smaller vessels. The Burmah-Shipment Channel, illustrated in Figure 11, leads to a harbor for small ships that was dredged from the coral behind the berth. The turn required by this snaky entrance is difficult, at best. A rather different approach is shown in Figure 12. This entrance would have been simple and straight, but unforgiving. Plans to develop a terminal and refinery at this location in Machiasport, Maine, were finally abandoned.

Three stages in the growth of a river port can be seen at Bilbao, in Spain (Figure 13). The latest requires a huge double-arm breakwater. Berths for the large ships are just behind it. Entering is somewhat like threading a needle, but once inside, there is ample

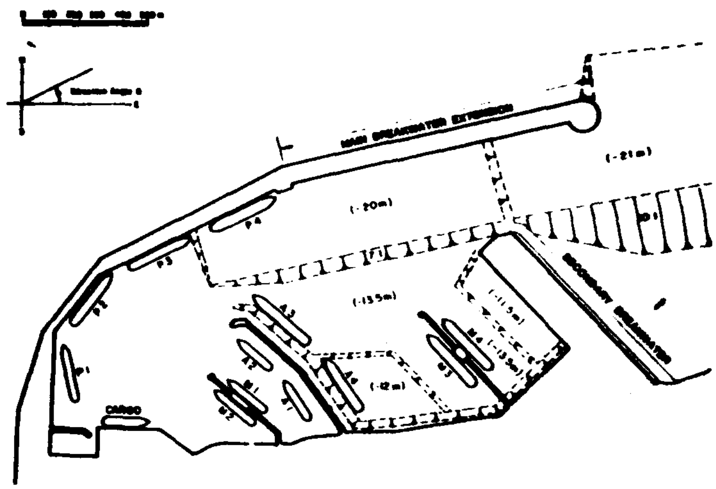

Figure 3. Harbor entrance with breakwater parallel to coast.

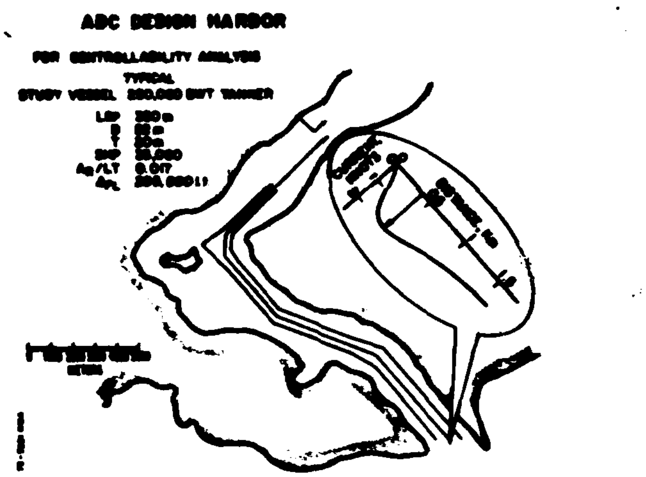

Figure 4. Test harbor for evaluation of tanker maneuvering.

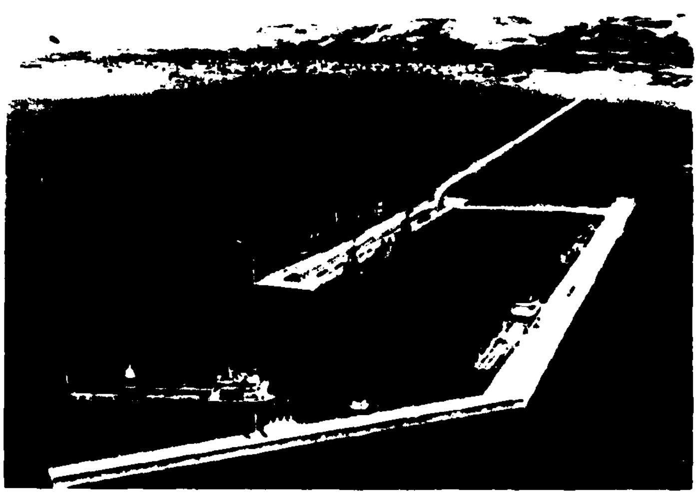

Figure 5. Entrance to harbor of Manfredonia.

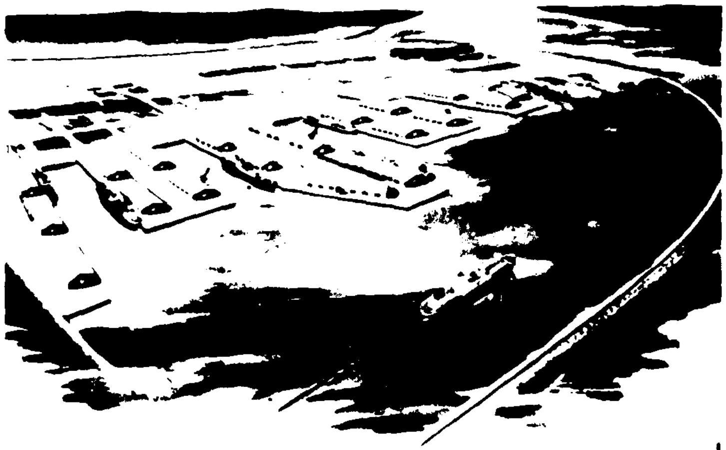

Figure 6. Harbor of Ashod, Israel.

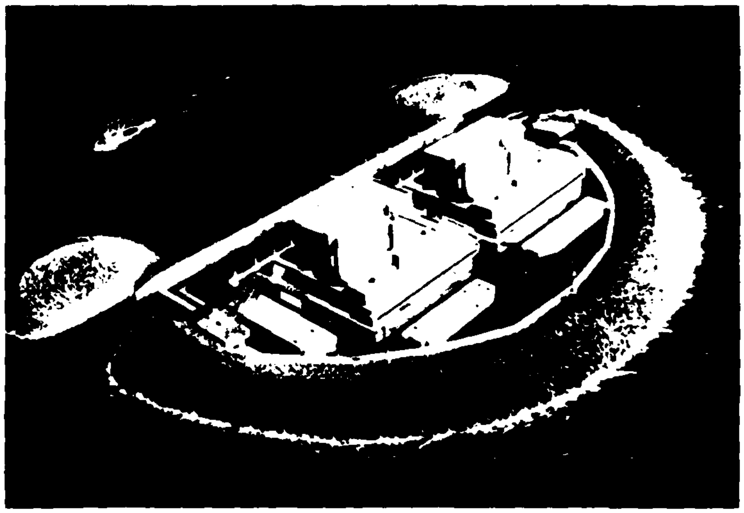

Figure 7. Dual entrances to power-plant island.

Figure 8. Simple entrance to pleasure marina.

Figure 9. Sea berths protected by rocky islands.

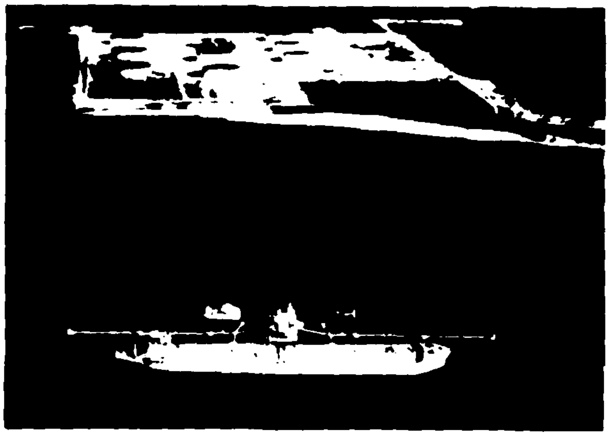

Figure 10. Sea berth for tankers, Grand Bahama Island.

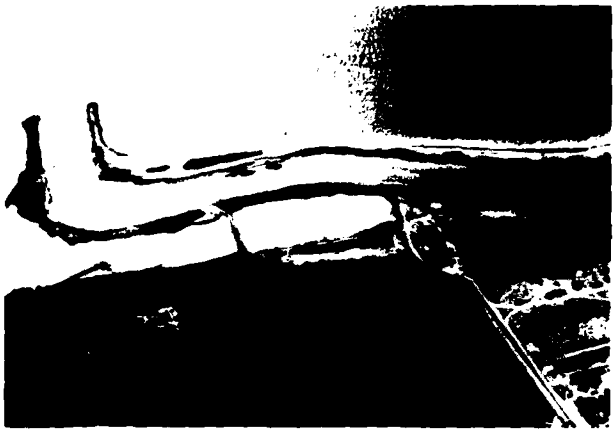

Figure 11. Burmah-Shipment Channel for small ships, behind berths of Figure 10.

Figure 12. Simple, straight, but unfortunate entrance to port.

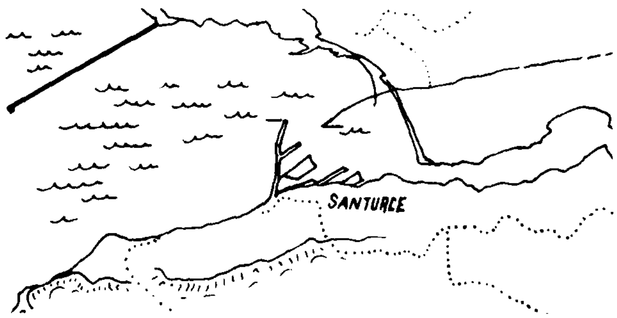

Figure 13. Port of Bilbao, Spain--difficult entrance to an ample harbor.

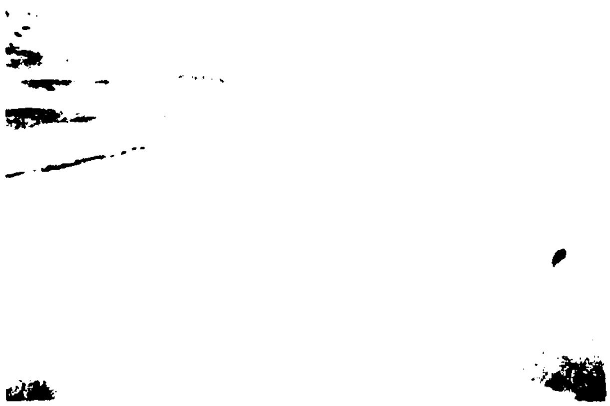

Figure 14. Entrance to East Rota Harbor, Spain--wide and easy.

room to maneuver, provided the tugs are available. For contrast, Figure 14 shows the wide, easy entrance to East Rota Harbor in Spain and its hook-shaped breakwater.

Figure 15 pictures the port of Bandar Abbas, Iran. A major consideration in the design of its entrance was the current velocities at the openings of the proposed breakwaters. Studies conducted at the Delft laboratories in Holland helped indicate how changes in the configurations of the breakwaters and channels could create better conditions. Another example of the consequences of breakwater design is illustrated in Figure 16. The long, straight breakwater at Escombreros, Spain, with berths on the inside, demands a curving approach by loaded tankers, and tug assistance to move the vessel laterally. Figure 17 shows the Port of Los Angeles, California, behind the big San Pedro breakwater, and its several channels. A proposed oil terminal for Los Angeles, sketched in Figure 18, would make it necessary to turn a tanker 90 degrees immediately after threading the needle at the harbor breakwater.

Port Aransas, Texas (near Corpus Christi), has a long, straight, dredged entrance between twin jetties that leads to the large turning basin (2200 ft) indicated in Figure 19. A similar design can be observed in Charleston, South Carolina (Figure 20). Notice how much shorter the twin-jetty entrance is than that of Port Aransas. This entrance is subject to shoaling from littoral drift through the inner, permeable portions of the jetties.

Figure 21 depicts Riviere-au-Renaud, Quebec--a narrow slot through a rubble mound, with the wharf just inside. The proposed industrial island and port illustrated in Figure 22 would have vessels entering from the left and exiting on the right. The curving approaches would require considerable skill to navigate. Another curved opening is Port Valdez, Alaska (Figure 23). Notice that the excellent natural protection of this landlocked bay is gained through the Valdez Narrows, and that they are narrowest at exactly the point where the separation of ship traffic ends. The entrance to the Suez Canal is also quite constricted, as can be seen in Figure 24. A recent planning study indicates there is little room for expansion.

Two long, straight entrances are illustrated in Figures 25 and 26, the Misurata Iron and Steel Port in the Gulf of Sirte, Libya, and the approach to Freeport, Texas, which meets the Intracoastal Waterway at a turn in the channel. A long course through ice-bearing waters leads to Melville Island, Quebec (shown in Figure 27).

A very open entrance (Figure 28) is that of Sines, Portugal, located behind a huge, rubble-mound breakwater. The design and master plan are being restudied because of severe damage to this structure. A design that also might be restudied is that of Kahului Harbor, Hawaii. The pincers-shaped breakwaters, drawn in Figure 29, have been repeatedly damaged at the roundheads. The displaced armor units can create dangerous obstructions at the channel edges.

Natural forces, as I pointed out, are always an important consideration in the design of entrances to ports and harbors. The entrance to Port O'Connor, Texas--Pass Cavallo--is actually a large tidal inlet (Figure 30). Acajutla, Salvador, was recently the subject

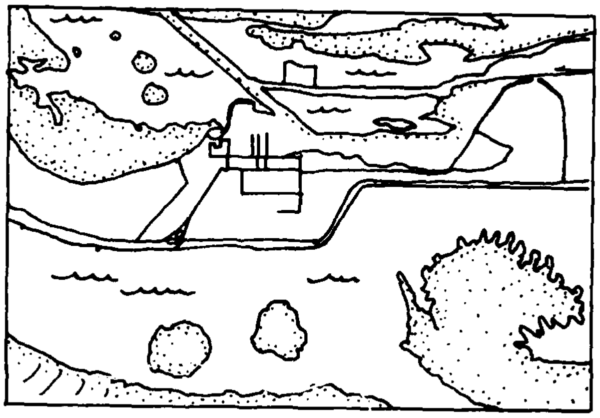

Figure 15. Port of Bandar Abbas, Iran, with breakwaters designed to minimize current velocities.

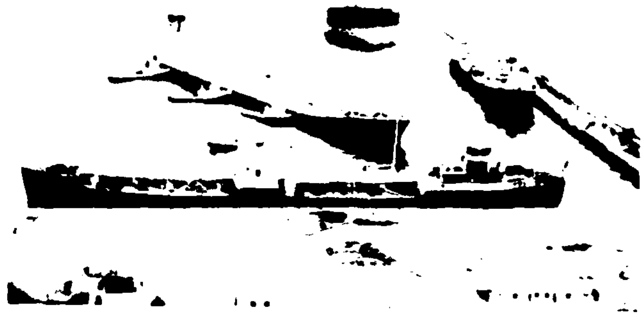

Figure 16. Straight breakwater at entrance to Escombreros, Spain, demands curving approach.

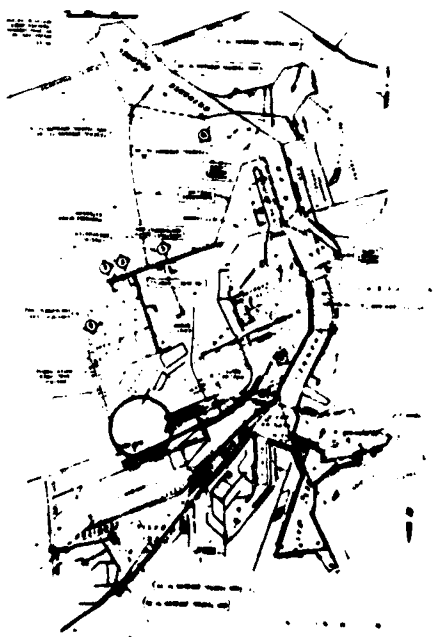

Figure 17. Port of Los Angeles, California

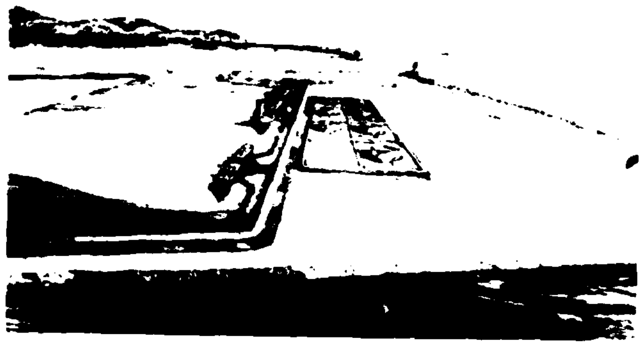

Figure 18. Proposed oil terminal for port of Los Angeles.

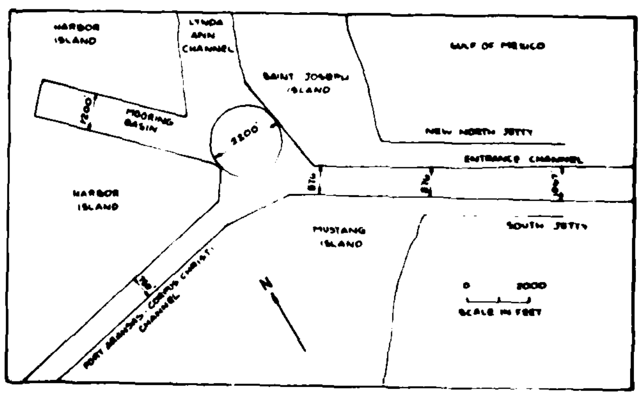

Figure 19. Entrance and turning basin, Port Aransas, Texas.

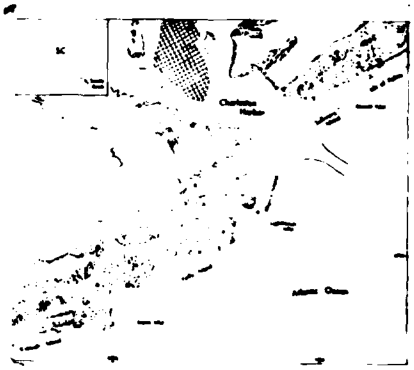

Figure 20. Entrance to port of Charleston, South Carolina.

Figure 21. Riviere-au-Renaud, Quebec.

Figure 22. Proposed industrial island and port--curved entrances would be challenging.

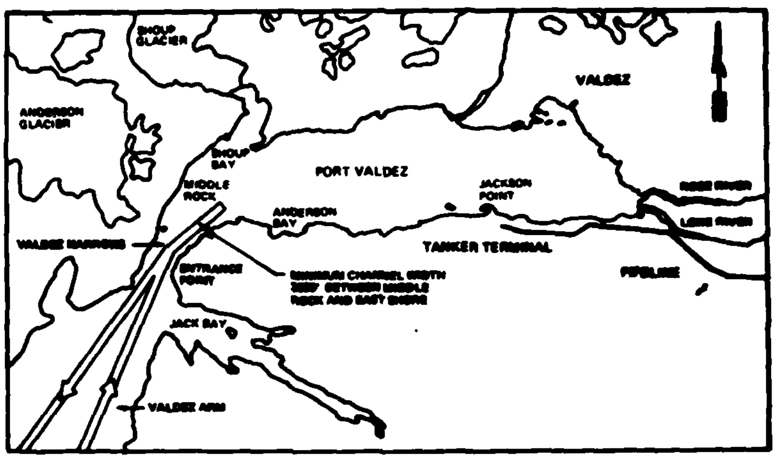

Figure 23. Curved entrance and narrows leading to port of Valdez, Alaska.

Figure 24. Constricted entrance to Suez Canal.

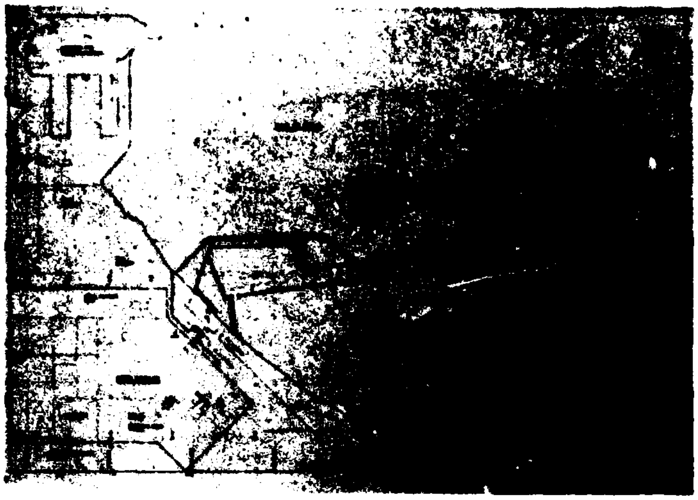

Figure 25. Long, straight entrance to Misurata Iron and Steel Port, Sirte, Libya.

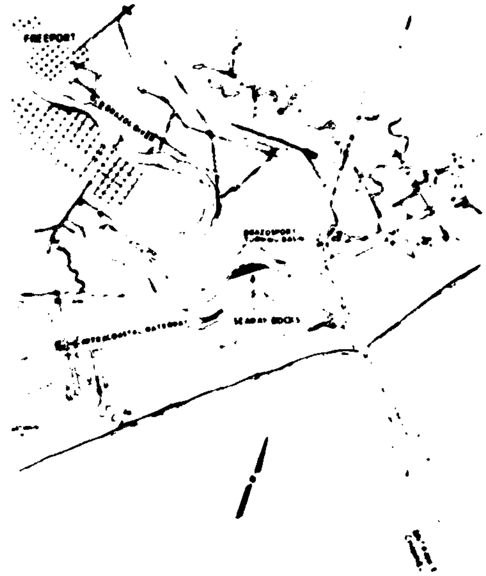

Figure 26. Another long, straight entrance, Freeport, Tex.

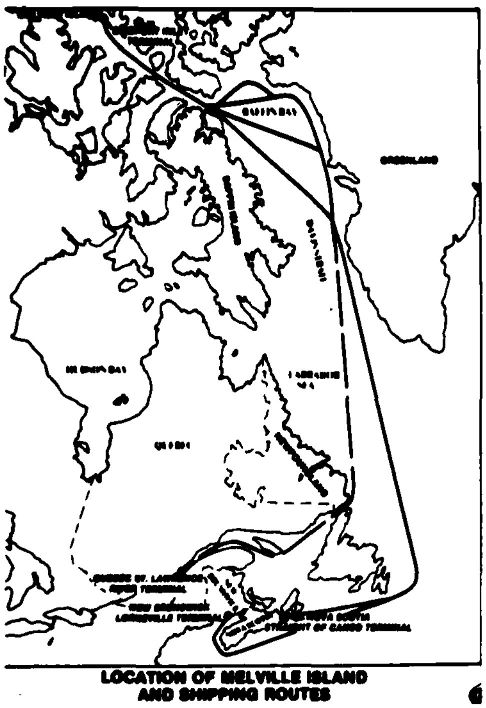

Figure 27. Long entrance to Melville Island, Quebec.

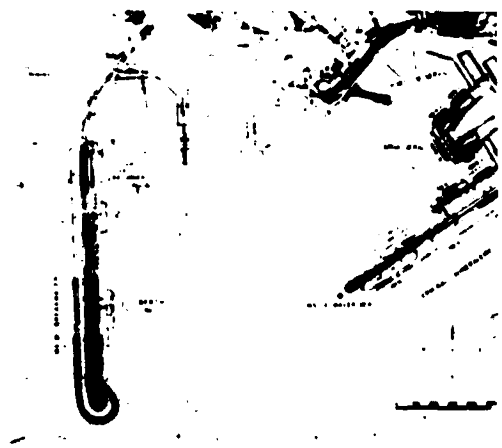

Figure 28. Open entrance to port of Sines, Portugal.

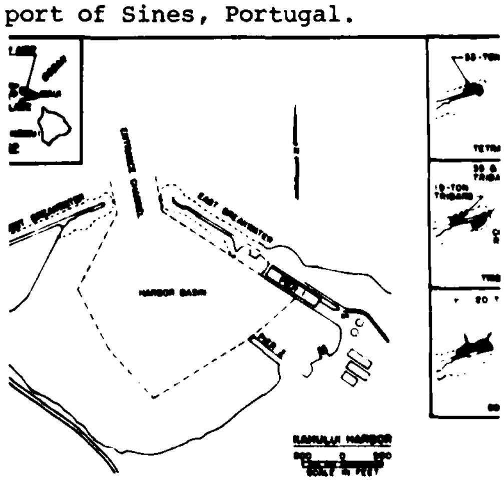

Figure 29. Pincers breakwaters of Kahului Harbor, Hawaii.

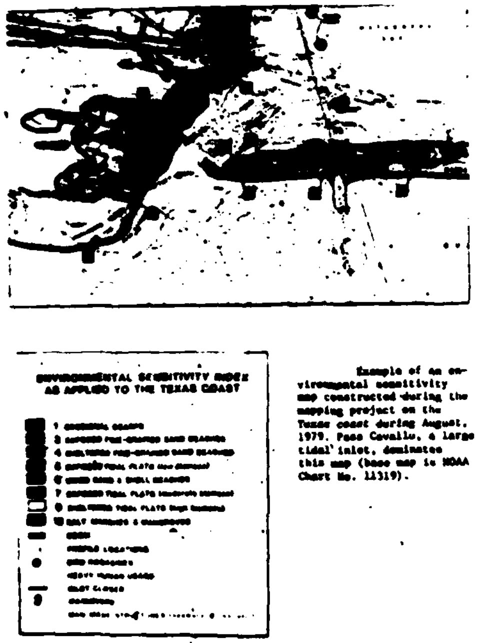

Figure 30. Tidal-inlet entrance to Port O'Connor, Texas.

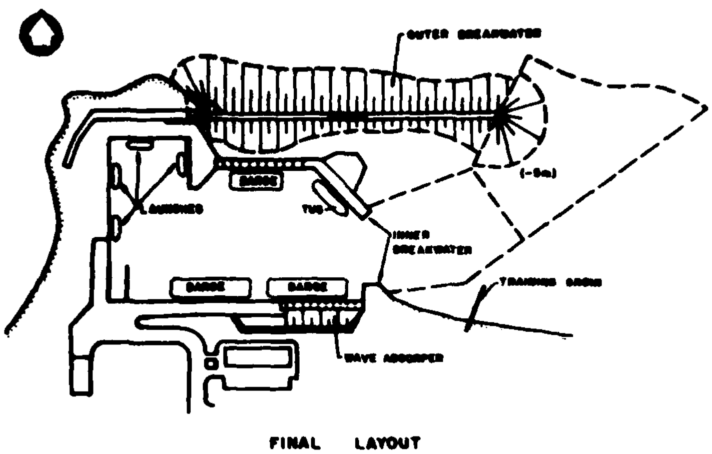

Figure 31. Harbor designed to reduce wave penetration for barge anchorage.

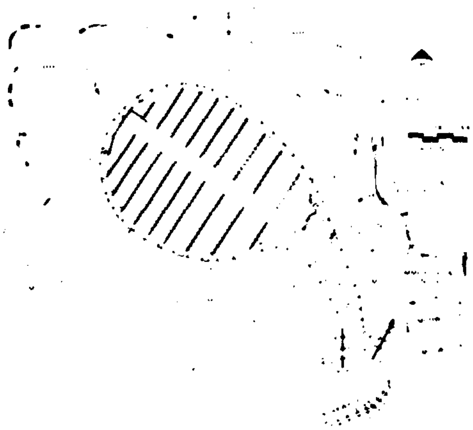

Figure 32. Marina harbor designed for minimal harm to environment.

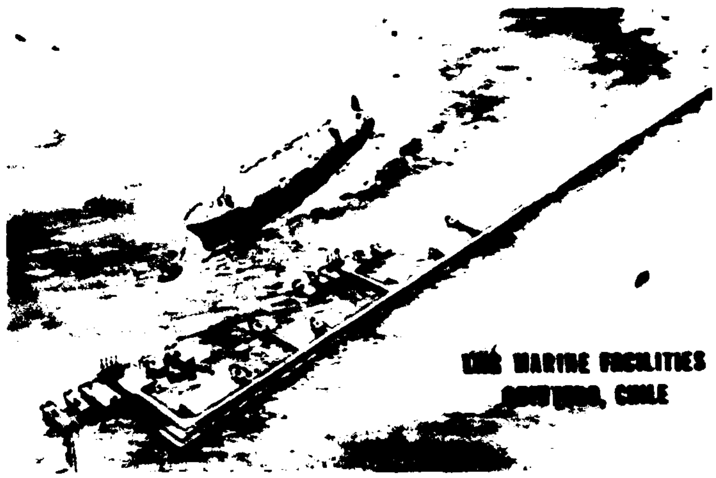

Figure 33. Tug assistance required to maneuver vessel through harbor entrance.

of exhaustive studies of harbor oscillation, a special kind of water movement characterized by large lateral and small vertical amplitude. Figure 31 illustrates a harbor designed after studying the wave conditions of a particular area. Outer and inner breakwaters provide quiet water for barges. In Puget Sound, on the other hand, the principal concerns in the design of a marina at Point Roberts (Figure 32) were the effects on the environment in this residential area, and protection against shoaling from littoral drift.

The last illustration, Figure 33, although not strictly of a harbor entrance, indicates the kind of difficult maneuver, with tug assistance, that many require. One hopes the vessel is going full astern at this point in its approach.

RULES AND REGULATIONS
GOVERNING ENTRANCES TO PORTS AND HARBORS

Captain Daniel Charter

This paper focuses on the regulatory issues relating to the safety of entrances to ports and harbors, particularly navigation safety. These regulatory issues include actions by international bodies and the federal government. This paper also briefly touches on state and local requirements.

One major caution should be noted here. The regulator at all levels of government, as a general rule, takes port and harbor entrance design as given, and develops suitable regulations and procedures around it. Certainly regulatory problems should be considered during the planning and design stage. However, the fundamental consideration should be navigation safety, rather than the regulatory aspects.

International Rules

There are several requirements at the international level that have an indirect effect on entrance design. The international requirements are generally for vessels. However, since the reason for the existence of a port is to provide an interface between land and marine transportation, it is obvious that regulatory requirements for vessels can influence port design considerations.

The first step is to determine the traffic mix that will be using the port entrance. Once this is done, the navigational equipment that vessels will be carrying can be determined by analyzing international carriage requirements. For example, will vessels have radar, back-up radar, depth finders, radio direction finders, etc.?

International rules that should be considered include the agreement that has been reached on standard routing measures for vessels, including traffic separation schemes. A traffic separation scheme is designed to separate traffic in congested areas, and generally to provide for inbound and outbound lanes, often with a precautionary area where traffic patterns cross. The overall port entrance design must then consider anticipated traffic volumes to determine whether a traffic separation scheme will be required. If one is required, is there room to accommodate both inbound and outbound lanes and still provide the necessary separation buffer? Will there be special types or sizes of vessels? Will there be cross traffic, and if so, what will

be the density and the types of vessels involved? Can these vessels be safely accommodated? Should the design be altered to permit a safer situation? Finally, coastal states have the responsibility to provide aids to navigation that permit vessels to use a traffic separation scheme properly. Does the overall design consider these aids?

International collision regulations should also be considered. While the collision regulations generally have sufficient flexibility to permit application to any entrance design, the planners should be aware of the regulations and avoid any design feature that would interfere with application of normal sailing rules. Legislation is pending in Congress that would unify the rules of the road for the United States and bring them into accordance with international rules.

As indicated earlier, international requirements apply to vessels rather than ports. There are a few exceptions, such as those I will note in a subsequent section. There is now an international convention in the process of ratification by the U.S. that enjoins governments to provide adequate reception facilities for oil, chemical, and other vessel wastes. An international guide is being drafted for port rules pertaining to the movement and handling of dangerous goods. However, there are no international proposals that would address port or harbor design or capabilities.

Federal Regulations

At the federal level, additional regulations are in force that primarily address vessel operations, and in some limited cases, special equipment requirements. These regulations can be found under Title 33 of the Code of Federal Regulations (CFR). The Port and Tanker Safety Act of 1978 (P.L. 95-474) provides broad authority to the Coast Guard to control vessel and waterfront facility operations, to establish vessel and facility equipment requirements, and to manage traffic in our waterways. It requires regulatory action that has not yet been completed for port access routes, pilotage requirements, and lightering zones.

Vessel equipment requirements and operating procedures are contained in the Navigation Safety Regulations (33 CFR 164). The equipment requirements are similar to the international requirements, except that the United States requires an electronic position-fixing device (either loran-C or transit satellite receivers satisfy the regulatory requirement) on vessels of 1600 gross tons or more. The principal purpose of this requirement is to assure safe navigation in the coastal confluence zone. However, the availability and accuracy of electronic positioning systems could be a factor in approach design. Navigation equipment requirements serve only one purpose today--to assure that the vessel is suitably equipped so that the mariner can properly navigate his vessel. The Coast Guard intends to publish a proposed rule requiring loran-C capability and a suitable device for retransmission of the loran coordinates to a shore station. The purpose of this requirement is to permit the Coast Guard to monitor the movement of a vessel during its approach to the entrance of Prince

William Sound, and its passage and transit. This proposed rule would apply only to tanker traffic in and out of Valdez, Alaska, but it is reasonable to expect that similar action may be taken elsewhere.

Although Prince William Sound is the only area where monitoring of vessel movements through equipment installed on the vessels is being seriously considered, there are other areas where vessel positions are monitored by radar or low-light-level television. These areas have established vessel traffic centers to provide vessels with information on the location and activity of other vessels. The vessel traffic center receives reports from vessel pilots. In some areas, it is necessary to augment these reports with some form of surveillance; to date, either shoreside radar or low-light-level television.

Although the need for a vessel traffic service (or VTS) is determined by casualty history, the existence or potential establishment of a VTS should be considered during entrance design. For example, the presence of a VTS would permit management of a one-way traffic flow if the design of the entrance makes it necessary. Absence of a VTS would not rule out management of one-way patterns. There are areas where management is exercised by local harbor masters or the vessel pilots themselves. The regulations governing mandatory participation in a VTS are found at 33 CFR 161. The rules of voluntary participation are covered in locally published operating manuals. Voluntary VTS systems are not covered by federal regulation. The following ports or harbors operate a VTS: Prince William Sound, Puget Sound, San Francisco, Houston-Galveston, and New Orleans. A limited VTS operation may soon be established in New York.

There are several other regulations pertaining to vessel management that could affect port and harbor design. These include anchorage regulations, security zones, regulated navigation areas, safety zones around offshore structures, inland waterways navigation regulations, and general safety zones.

The anchorage regulations (33 CFR 109-110) establish anchorage grounds, specify their limits, and prescribe management procedures, if necessary. An anchorage can be relocated or abolished, so it need not be a constraint in entrance design. However, an existing anchorage was established for some purpose, usually to serve as a holding area for queued vessels. If an anchorage must be changed in reconfiguration of a waterway, its use must be analyzed so that alternatives can be provided if necessary.

Security zones (33 CFR 127) are established to safeguard vessels, harbors, ports, and facilities from destruction, loss, or injury from sabotage. Entry to these areas can be made only with permission. While there are very few of these (five now exist) the presence of a security zone and the conditions governing operations within the zone could have major implications for entrance design, and the regulations should be checked for the area in question.

Regulated Navigation Areas (33 CFR 128) are designated for specification of navigation rules to be observed when operating in areas that present unusual hazards. When such an area is established at a port or harbor entrance, it is usually due to a basic design problem. The existence of Regulated Navigation Areas must be

considered in new designs. It would be desirable to eliminate the conditions that prompted the regulations, but even if this is not possible, awareness of the regulations and reasons for them should provide the designer with insight into problems that might be encountered.

Safety zones on the outer continental shelf (33 CFR 147), inland waterways navigation regulations (33 CFR 162), and safety zones in navigable waters (33 CFR 165) could also affect entrance design, and it would be a good practice to check these parts of the regulations. It may be that the factors that prompted regulatory action could also influence entrance design. This is particularly true in the case of the regulations for inland waterways navigation, as these specify conditions for some locations that are very similar to the rules for Regulated Navigation Areas.

As previously mentioned, several sections of the Port and Tanker Safety Act will ultimately lead to regulatory action in pilotage requirements, port access routes, and lightering areas.

The pilotage requirements can be confusing, particularly since they involve some departure from traditional federal-state relations. Another presentation addresses these concerns ("Harbor Entrance Design: A Pilot's View"). Designers of harbor entrances should be aware that the regulation of pilotage may come under the administration of either the federal or state government, depending on the nature of the trade and state requirements. Pilotage requirements for vessels engaged in coastal trade is a federal function, while primary authority for pilotage on vessels engaged in foreign trade is vested in the states. There is a provision that the federal government may require pilotage when the state government does not, but no federal regulations have been issued under this authority.

The Port and Tanker Safety Act provides for establishment of lightering areas where vessels can transfer oil and hazardous commodities from ship to ship. This provision was included in the act primarily to provide areas for transfer of oil from ULCCs (ultralarge crude carriers) and VLCCs (very large crude carriers). No such areas have yet been established, but a notice of proposed rulemaking is expected to be published in the near future.

Although the lightering areas themselves probably would not affect entrance design, designers should maintain awareness of their location and activity. Lightering activity can have a substantial influence on the traffic patterns in and around port entrances.

The final area of the Port and Tanker Safety Act that I will address in this section is port access routes. As the number and variety of demands for the available space on our offshore waters increased, conflicts began to arise among the users. The first offshore structure, probably even the first several hundred structures, were helpful to the mariner in fixing his position. With the placement of several thousand structures, they soon became a major hindrance to navigation.

As a result of these and other conflicts, Congress ordered a study of safe port access routes and the publication of suitable regulations that would recognize the paramount right of navigation over all other

uses within the designated area. Studies of some of the high-priority areas will be completed this year. Establishment or potential establishment of access routes under this authority will have major consequences for entrance design. When study of an area has been completed, regulations will be published in the Code of Federal Regulations. If there are no regulations for an area, there may be an ongoing study to establish whether such regulations are needed, and if so, what they should specify. This can be determined by checking with the local district office of the Coast Guard. If a project involves the redesign of a port or harbor, it could change the existing traffic patterns, and this may necessitate reexamination of an already completed study of port access routes. If this is the case, the district office should be consulted so that suitable safe access routes can be established, if necessary.

State and Local Regulations and Customs

I have indicated that entrance design can also be affected by state and local regulations. While these vary from port to port, they are generally similar to federal regulations.

As noted, the bulk of the pilotage requirements are under state jurisdiction. Although some actions of state and local authorities are preempted by the federal government, these governments and regional authorities may impose certain vessel operating controls, and operate the equivalent of a vessel traffic service.

In addition to the actual local requirements, in many waterways there are binding procedures resulting from local customs or practices. Observance of these may be as important or more important than observance of the formal regulations. Most of these local practices are given in the appropriate Coast Pilot and suitable charts of the area, or they can be obtained by consulting with the local pilots associations.

Summary

Most of the rules, regulations, and customs governing the entrances to ports and harbors were developed in response to the design of the entrances (either natural or man-made). However, one or more of these requirements could have substantial importance for entrance design. While rules and regulations are flexible and can be changed to meet the requirements of new or redesigned entrances, it may well be that the factors creating the need for the regulation cannot be changed. Therefore, the examination of applicable regulations in project planning should include analysis to determine why they were required. If a project will affect existing regulations, contact should be made as early as possible with the appropriate authorities so that necessary actions can be initiated.

DISCUSSION

KRAY: Aside from the regulations for aids to navigation, what is the Coast Guard's jurisdiction over drawbridges, particularly their engineering for maximum navigability?

CHARTER: We issue the permits for bridges over navigable waters. As part of the process, we review the implications of the design for the navigable water body. We examine the design for other effects as well, and go through a full environmental analysis or environmental assessment during the process. A major item of the design review would be the effects of that particular bridge on the safe navigation of the water body.

This is a function that was fairly recently (in the mid-1960s) transferred from the U.S. Army Corps of Engineers to the Coast Guard.

There is an aspect of the bridge problem that might be of interest to you and others here. If any of you have used our waterways, particularly the inland waterways, you are well aware that many of the existing bridges--bridges that have been there for 50 or 75 or more years--are obstructions to safe navigation. There is provision for the federal government to modify or to require modification of these bridges, using primarily federal funds, with some funding from operators for the modifications. Several dozens are identified as hazardous to navigation, and a single modification project might cost $10 or $20 million. It is a very expensive process.

KRAY: The second question I have is, I understand that the port of Galveston is enlarging its facilities and trying to construct deepwater ports. I would like to know how far the Coast Guard is involved in approval of the design of that navigation channel.

CHARTER: We were involved in the review of the project proposal from the point of view of navigation safety. We did provide some comments on aspects of navigation safety, the relationship of the proposed project to the port entrance itself, and the traffic patterns in the area. Some of the problems we perceived had to do wih the design of the channel in relation to the traffic flow.

HERBICH: During the last six-month period ending about February 1, there were 18 ship collisions or casualties around Galveston. We have formed some opinions about why this occurred. I wonder if you might have some opinions.

CHARTER: The Coast Guard has written a 103-page opinion on that particular subject. One of the provisions of the Port and Waterways Safety Act of 1972 is authorization for the Secretary of Transportation to ,nduct investigations of general casualties. We have long had the authority to investigate vessel casualties, but in the new act the secretary was given specific authority to investigate casualties not necessarily related to vessel collisions, ramming, or groundings.

Under that authority, we conducted our first investigation very recently, and it was of the Galveston channel entrance. We felt that a number of occurrences there were not justified by the density of traffic and the traffic mix.

As a result, we convened a board and the investigation was conducted. It was completed approximately two months ago. The investigative report was circulated to the offices in our headquarters and also to our district office and local units for comment.

Several comments have been received, but the final commandant action has not yet been taken. The board has many recommendations--perhaps 30 or 40. Most pertain to the aids to navigation, the traffic flow, and the vessel traffic management in the area.

I would say that 80 percent of those recommendations will be acted upon by the Coast Guard. Some depend on the action of other agencies. Among the recommendations that will likely appear in the final report are provision of a traffic separation scheme with a suitable precautionary area, looking at the pilotage boarding location and the entrance aids to navigation, particularly the channel marking aids, and others. The investigation was triggered by the similarity of the incidents as much as by their seriousness.

WEBSTER: I gather from your comments that vessel controls are installed and Regulated Navigation Areas established only after there have been some casualties. My question is, do you use any of the simulation techniques that are now available to evaluate harbors and navigational aids?

CHARTER: I think there will be a presentation that discusses the use of simulation techniques for harbor entrance design and aids to navigation. I use it as part of the decision process. I start basically with casualty history, because we have to demonstrate a favorable benefit-cost ratio. Any of the installations we are looking at must be justified to our own department and agency, the Office of Management and Budget, and Congress. Although we are working on several other approaches, the only way we can justify the cost of a vessel traffic system or other traffic management control techniques is through historical analysis of the casualties, and projection into the future of the cost of doing business in that area, and the potential benefits.

Probably the most complete analysis we have done--and are still doing--is for Puget Sound. We looked at the historical analysis of casualties, and spent a great deal of time at the computer simulator in Kings Point examining different sizes and types of vessels, and different operational control techniques to determine the operational controls that would assure safe navigation under all conditions.

The exercise for Prince William Sound was very similar. The problem is that for a single regulatory action in Price William Sound and one in Puget Sound, the research, the studies, the background investigation alone cost a couple of million dollars.

I try to structure these studies so that the results will be widely applicable to navigable waters. I would hope that the risk analyses we are conducting for Puget Sound, and the tug-assist trials taking place in October and November, would transfer almost totally into any environment.

I don't know if we will be completely successful, but these are among our goals.

HARBOR AND PORT AIDS TO NAVIGATION

Commander Guy Clark

Aids to navigation are devices external to vessels that are designed and placed to help mariners in the safe navigation of their vessels. The mariner has two concerns in navigating the entrance to a port or harbor: first, avoiding collisions with other ships, and second, knowing where the vessel is on the face of the earth relative to fixed hazards. This latter concern--positional navigation--is addressed by harbor and port aids to navigation.

Perhaps the first aids most people think of are lighthouses, buoys, and lightships. As there is only one lightship station left in the United States, the lightship is almost a thing of the past. The aids we provide are planned as co-located systems of signals--a daytime visual system, for example, and a nighttime visual system. There are also electronic signals--racons and radar reflectors to assist radar navigation--radio-navigation systems, and of course, traditional sound systems for warnings of last recourse. It is most convenient to co-locate these systems. The buoy marking the Galveston Bay entrance, for example, is equipped with a light for nighttime visibility and a structure for daytime visibility, racon and radar reflectors, and a whistle.

These aids to navigation are passive: they do not replace the navigator. It is hoped that mariners will use them for their intended purpose, but the investigation of casualties often indicates that the aids provided were not used, or that they were not used properly. This, together with the fact that the Coast Guard provides and maintains more than 50,000 aids at a cost of more than $100 million a year, raises the questions: What systems are most important? Which do mariners need most?

The answer is complicated by the fact that mariners sometimes use one system, and at other times, another. A system that serves perfectly well in some conditions may be inadequate in others. Recreational sailors seem to like buoys because they're unmistakably nautical, particularly if a pelican or seagull is perched on top, but in our opinion, buoys are inferior to fixed beacons as aids to navigation.

Ten years ago, the Coast Guard initiated a program to replace buoys with beacons for greater economy as well as better navigational service. There were many objections, and some serious problems. We

found that tugboats in certain areas used the beacons to assist them in negotiating their turns, leaning their tows against them and pivoting. A few 90° turns easily destroyed these beacons. As buoys are sometimes less expensive to replace than beacons, the Coast Guard has been forced to reverse its program in some areas.

The basic principles we follow in planning and placing aids to navigation in and near ports and harbors are to mark the channel and the safe passages, signal the presence of obstructions or hazards, and to respond to requests for additional aids wherever reasonable and feasible. We rely on knowledge, common sense, and experience. Having recently returned to Coast Guard headquarters as the Chief of the Signal Management Branch of the Short Range Aids to Navigation Division, I have been giving considerable thought to the need to improve our service to mariners, and to gain better understanding of the man-system interactions and other factors that are most important to navigation. Such considerations point to additional research, perhaps with the use of simulators. In its Latin roots, the word "navigate" means to go from place to place by ship, and from at least as long ago as the word's origin, mankind has searched for better ways to navigate.

DISCUSSION

WEBSTER: I would like to reiterate a question that has been asked of Captain Charter. In replacement of the buoys, you say that you do not use simulations to determine the best place for them, but rather mark areas where ships might go (or have gone) aground?

CLARK: We have been aware for some time that we need some type of analytical tool to compare one configuration of aids with another for a given harbor to determine which is better and whether the improvement is worth the difference in, say, cost. We did initiate a research and development effort to define the performance to be expected of aids to navigation, and to evaluate existing and proposed systems of aids.

The use of simulations is an interesting possibility that we may hear more about in the presentation scheduled on the subject of shipboard aids to navigation.

WIEGEL: In one of the panel's planning sessions for this meeting, a representative of the Coast Guard mentioned that one piece of information the navigator would like to have about an area is the prevailing currents. There are current charts, of course, but as you know, very often the difference between the actual and the predicted currents is significant. Has the Coast Guard given thought to placing current meters in certain critical channels that the ships could interrogate and get data back, for real-time information on currents?

CLARK: I am not aware of any plans to try such an arrangement, but they may exist. Speaking as a sailor, I always want

to have total knowledge of currents and other conditions that impart relative motion to the vessel, to compensate for it. Translating this desire into navigational aids, however, raises many questions about the kinds and amounts of information to be imparted, and the most useful ways of conveying or displaying it.

KNIERIM: What about the possibility of data-gathering programs that would give harbor pilots, for example, more accurate and complete charts of winds, waves, tides, and currents?

CLARK: I think that is a good point. The Coast Guard, to the best of my knowledge, does not maintain any tide or current gauges for the sake of providing information of this type. The ones I have seen have all belonged to other agencies. NOAA (the National Oceanic and Atmospheric Administration), of course, collects the information and provides tables. I think part of the question here is, if this is useful, who should be doing it?

LE BACK: It is not that expensive to do it. We did an extensive experiment in tidal analysis after two LNG (liquefied natural gas) terminals were built, and we developed a set of tables for the pilots that enabled them to judge wind direction better, as well as the various stages of the tide, and what the current was doing.

I don't think this should be done by the federal government. The government can bog itself down in a million-dollar study of something that would cost a private operator or port authority perhaps four or five thousand dollars. Port authorities should conduct such programs and make the information available to the users.

MAINTENANCE DREDGING

John Downs

Dredging serves the objectives for which ports and harbors (and by inference, their entrances) are designed and constructed, by creating and preserving specified configurations of channels and sheltered areas for the safe conduct of marine traffic. Dredging operations remove the materials, principally soils, that collect on the bottoms of these areas. These seemingly simple tasks, conducted in the marine environment, demand large capital investment in equipment. A sufficiently clear set of national objectives is needed to allow the specification of equipment, its acquisition, and plans for the order and management of operations to be carried out well in advance of undertaking these tasks. An important aspect of the national objectives affecting dredging is a set of guidelines for the delivery or disposal of dredged materials. In day-to-day operations, the same kinds of physical environmental information required by mariners are vital to the operators of dredging operations. Thus, the subjects addressed in the three categories of this meetings' concerns--design and maintenance, the concerns of ships and users, and nature and the environment--are all important to dredgers, and the operations of dredgers are important to realizing (or failing to realize) the objectives that might be set in these categories.

These facts would seem to dictate the closest collaboration of all interested parties, yet there is a critical lack of integrated planning and management of this country's ports and harbors. The nation faces serious imbalances in the energy resources it imports, such as foreign oil, and its abundant energy resources for which there is growing foreign (and little domestic) demand, namely coal. Resource economists agree that no ready substitutions will replace imported oil for the next ten to fifteen years. Other nations are fully prepared with large ships and deep-draft receiving facilities for our coal. Yet, this country has no deep-draft harbors sufficient to this much needed trade. Viewed from the national level, plans and actions to create deepwater ports, or offshore facilities, have been spasmotic.

The critical lack of communication and coordination is evident in the long-standing concerns the dredging industry and the U.S. Army Corps of Engineers, environmentalists and preservationists, and citizens have long had for the effects of various means of disposing of dredged materials. After an intensive five-year study of all aspects

of this subject that included the development of a new piece of equipment to reduce turbidity, careful monitoring of specific disposal methods in well-studied sites, and the publication of more than 100 documents (including guidelines for the multitude of various situations that might be faced), the results are still unknown to the state and local governments that have held up improvements to ports and harbors that imply significant dredging.

The disposal of dredged materials with care and judgment can be beneficial or innocuous to the environment--restoring eroded beaches and creating new habitats, or harmlessly entering the deep ocean. Contaminated materials need special care, and the disposal of these is addressed in detail in the reports of the Dredged Materials Research Program reports (sometimes called the "WES reports" because they were supervised by the Waterways Experiment Station of the U.S. Army Corps of Engineers).

There is some resistance to these reports, where they are known, owing to an inferred conflict of interest in the Corps' having supervised them. Although the studies were coordinated with the U.S. Environmental Protection Agency, the Corps of Engineers is both a dredger and a major contractor for dredging services, and there is some feeling that the Corps' environmental assessments cannot but serve the interests of continued dredging.

Coordinated planning and management of port and harbor projects would allow environmental and economic interests to be aired and afford better opportunities for satisfying both. On faith alone, for example, that the country would realize its pressing need for improved facilities, the dredging industry has invested large sums in up-to-date equipment. These are now being deployed in projects worldwide--projects far more sophisticated than any undertaken here--but the anticipated domestic activity has not yet begun. The present situation is that supertankers and large cargo ships requiring drafts of 60 feet or more cannot enter our ports and harbors. The maximum permissible drafts of our domestic ports and harbors are 38 to 43 feet.

Some state and local governments and port authorities have advanced plans to deepen facilities, or to improve their dimensions. These plans are frequently frustrated by the financial arrangements necessitated by legislation for such public works, assuming the plans pass all the other obstacles and tests.

Summary

The problems faced in the prosecution of maintenance dredging programs are principally administrative and political, not technical. Several companies in the industry have scheduled work that later could not proceed for lack of necessary permits. Much of the legislation seeking to protect the environment from the effects of dredged materials appears now, in the light of comprehensive studies, to have been premature. The nation has urgent needs to improve the dimensions of its port and harbor facilities, and it has been demonstrated, but not communicated widely, that careful site-by-site evaluations and judgments can be employed to prevent significant harm to the

environment from dredged materials. Yet, the lack of coordinated planning and management of these harbor and port developments results in failure to follow through in action.

DISCUSSION

HERBICH: Over the years I have heard comments about the obsolescence of both the government and the private sector dredges What is your opinion of their present status?

DOWNS: I won't comment on the public sector's dredges. I will say for the private sector that tens of millions of dollars have been spent in the last few years in the optimistic hope that ports will be maintained and that this country will continue to build new or improved ports and harbors.

Our role, as directed by the Congress, is to conduct as much of this activity as we possibly can, under the direction and management of the Corps. I don't think there is any question that we can compete in the world today, as we have shown by going overseas to work.

A great deal of money has been spent in other areas of the world. The Dutch have spent 100 million dollars on one dredge. We cannot meet this capability because there are no projects here that will support it.

BERTSCHE: Would it be appropriate in the design of new ports or for major modifications to ports to plan initially where the maintenance dredging spoils would be disposed of, or is that done now?

DOWNS: I wouldn't want to go so far as to say all maintenance dredging would be disposed of in the same place. Different materials demand different treatment. Certain virgin materials are put on designated islands. Bird sanctuaries have been created on some of these islands.

HERBICH: Suppose that there were three new harbors authorized, say, Galveston, Corpus Christi and perhaps another in the same area? Would the private sector have sufficient capacity to handle dredging or deepening of these three harbors?

DOWNS: When the contract comes out, the port authorities may want it done in 18 months, 20 months. We have tried to talk them into three seasons, which would be a little over 24 months, or perhaps 30. The timing of dredging operations is always critical: having the right set of dredges and other equipment at the right place, on time. In the instances you name, existing equipment could perform the closer-in work, and development could proceed for the equipment needed for the outer, deepwater portions. This equipment has been designed, and manufacture could proceed if the market were evident. For this equipment to be developed in a timely way, careful planning is necessary. Industry is looking forward to preparing for these developments, and I think it will not be found lacking.

CONCERNS OF SHIPS AND USERS

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CONCERNS OF SHIP OPERATORS

C. Lincoln Crane, Jr.

Basic Requirements at a Harbor Entrance

The three succeeding presentations address aids to navigation, ship controllability, and pilots' concerns. My topic is ship operators' concerns. While linked to the other subjects, operators' concerns can be surveyed most simply with two questions:

1. Does the harbor entrance provide sufficient horizontal (i.e., bank-to-bank) clearances under nonextreme conditions of wave, wind, and current?
2. Is there sufficient bottom clearance under the nonextreme conditions?

Answering these questions requires understanding the effects of a number of port-related factors, such as:

- Horizontal channel dimension (i.e., channel segment widths, and lengths and radii of bends),
- Channel depths,
- Regularity of bottom and banks,
- Water waves,
- Strength and uniformity of water currents, and
- Quantity and quality of information provided to the shiphandler regarding ship's position relative to all the above.

This list assumes that the ship has adequate inherent controllability, shipboard aids to navigation, machinery, communications, pilotage, and crew, all of which are outside the scope of harbor entrance design. Also assumed are adequate vessel traffic services and adherence to rules of the road.

Port Appraisal Methods for Harbor Entrances

How then can a ship operator objectively appraise a port to determine its suitability for a ship having particular dimensions? For horizontal clearances, he may take one of the following approaches:

1. He may transfer previous harbor entrance experience to his new situation. In other words, he may follow his own or industry practice at a similar port. Or, he may use previously documented channel design standards such as are available from PIANC*, the U.S. Army Corps of Engineers, and the Canadian Coast Guard.[1/2/3] However, these codes may not address the particular local issues in question, such as a locally high crosscurrent. Also useful may be the results of available ship-tracking studies made during port entry or departure, such as data taken at Southampton, Le Havre, and New York.[4/5/6]
2. Another option is to order a special hydraulic model study of specific port-entry situations, such as those involving large and variable currents, maneuvering at bends, and breaking waves at an entrance.[7]
3. Only in the last few years have real-time computer-based ship handling simulator studies become available, which include hands-on control by experienced ship handlers. Examples are recent studies conducted with large research simulators, such as those of the Netherlands Ship Model Basin,[8] CAORF†,[9] and the Swedish Maritime Research Center.[10] All such large facilities offer outside-view displays combined with carefully duplicated wheelhouse mockups, shipboard navaids, etc.
4. A number of less expensive real-time research simulators have recently been developed that employ cathode-ray-tube perspective scenes instead of outside views. These are supplemented with computer-graphic bird's eye displays that plot shoreline, aids to navigation, and the ship at closely spaced intervals. Under some circumstances, these simulators may satisfy all requirements, such as for appraising a new port-entry proposal relative to an acceptable base case.
5. A much faster and less expensive technique is also now in use that simulates the ship handler's actions by substituting an automatic control function mathematically. Such a function must account for the key cues and sensitivities of human pilots. Figure 1 illustrates the functions that a human ship handler performs when piloting a vessel, and that simulation of the ship handler must also supply to an appropriate degree. The full computer simulation is clearly limited to rather simple navigational situations, and in those, it has the advantage of allowing numerous orderly variations of main parameters. Examples are studies of the effects of changes in the direction and magnitude of disturbances such as wind and current.[9]
6. Methods of direct calculation have been applied in some harbor-entrance design projects, such as in the selection of approach-channel widths and aids to navigation at the new port for ultralarge crude carriers (ULCC) at Cape Antifer, near Le Havre. In that case, the "maximum variation" method developed by EASAMS, Ltd., of the U.K. was used (described by M. Ribadeaux Dumas in

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*Permanent International Association of Navigational Congresses
†Computer-Aided Operations Research Facility

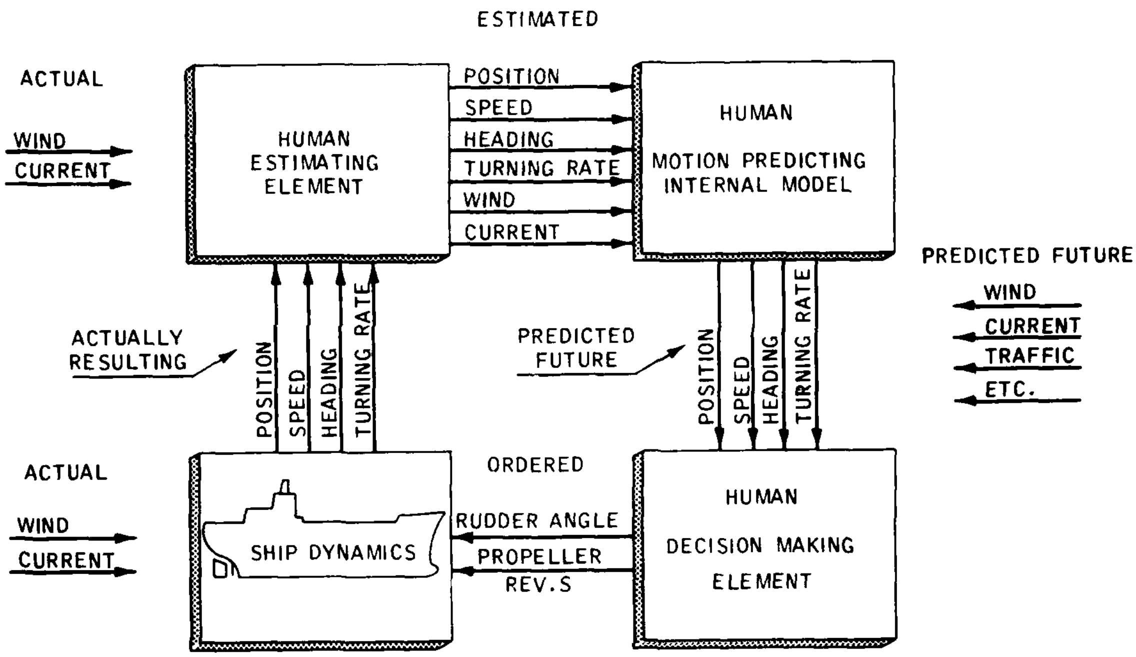

Figure 1

MAN-SHIP CONTROL LOOP

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reference 11). This method estimates the maximum variation of a vessel from its intended track due to the navigator's uncertainty of his position. The resulting overshoot motion of the ship in recovering and returning to the channel centerline is estimated in a paper analysis.

Turning now to bottom-clearance appraisals, there is again more than one available procedure. The simplest is, of course, direct local knowledge based solely on the experience of earlier ships in that area and the reports of pilots. Regarding analysis, the basic calculation is simply to subtract the ship's static draft at its lowest point from the calculated water depth at the shallowest spot.[1] Allowances are then made for ship sinkage and trim at speed, possible heel, ship motions in waves, tidal height, and bottom siltation and debris, as shown in Figure 2a. However, this calculation will produce overly conservative results because it assumes the coincidence of maximum excursions if simple algebraic addition of allowances is used. Therefore, statistical addition of allowances for each factor should be substituted (Figure 2b).

In very special cases, model or full-scale ship trials may be made to determine actual bottom clearances. This was recently done for the National Ports Council by the National Maritime Institute in England for ships entering Southampton, and for ships passing over the bar at the Columbia River entrance in Oregon.

Indices

Having predicted the horizontal and vertical ship-to-ground clearances, the operator will want to complete his appraisal by comparing the results to some standards. If results are positive, he may judge the port to be safe.

For horizontal clearance, the index should address the minimum bank clearances at the most critical points, such as:

- Where a ship is held close to one bank prior to entering a turn, or when preparing for an abrupt shear-current effect from that side;
- Where a ship is recovering from a turn in the channel, or after responding to a shear current;
- Where a ship's controllability is reduced by the need to decrease speed (hence, propeller rpm and rudder force);
- Where the ship normally passes other ships in a channel.

To judge the maneuvering safety of the candidate ship, the operator must then compare its expected performance against that of a base ship with which he is presently comfortable in the same situation.

For vertical (bottom) clearance the index will either be in terms of expected minimum bottom clearance (assuming that all anticipated clearance allowances are required at the same moment), or the probability of the ship's bottom coming within some small fixed distance of ground, say once in every "n" passages.

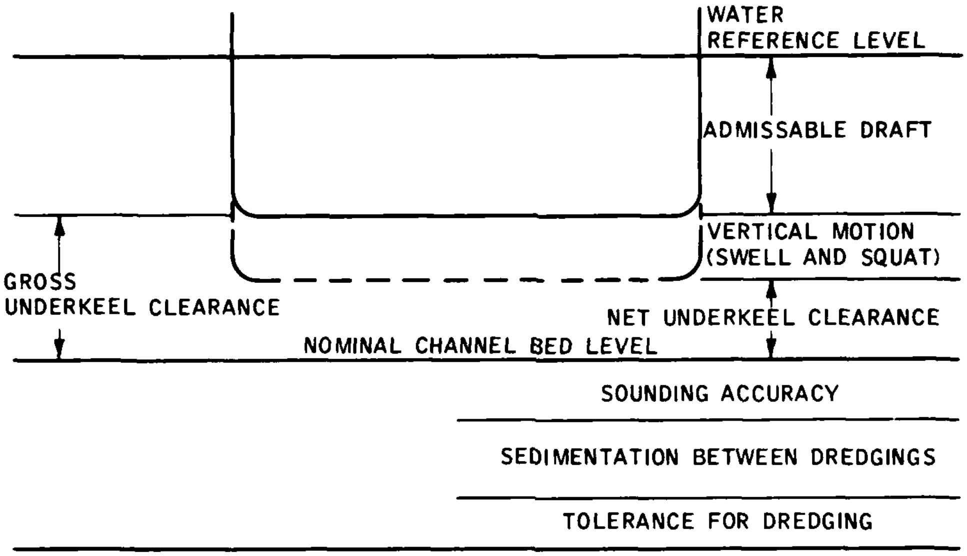

Figure 2a

CONVENTIONAL NET BOTTOM CLEARANCE
CALCULATION - DEFINITIONS
(FROM PIANC, REF. 1)

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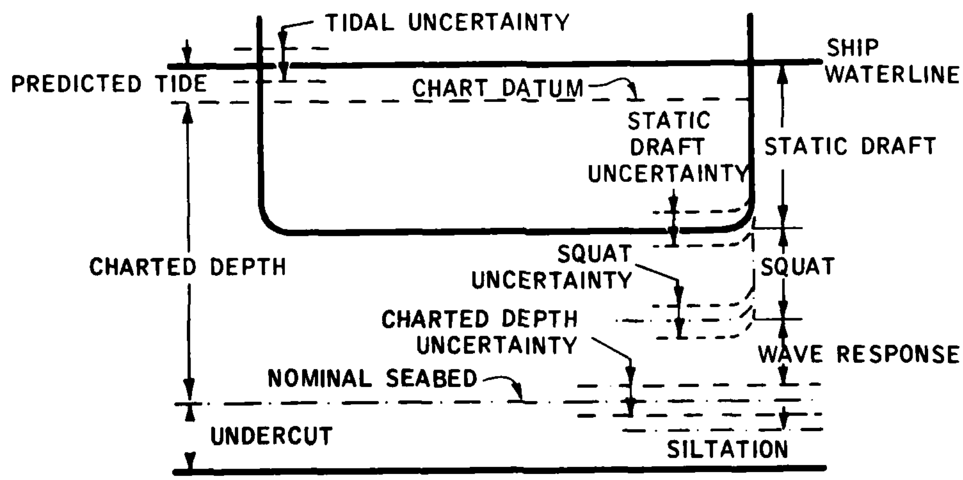

Figure 2b

STATISTICAL BOTTOM CLEARANCE
CALCULATION - DEFINITIONS

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Limitations of Present Study Methods

Several methods for appraising the adequacy of horizontal and vertical clearances have been mentioned here, yet none is entirely adequate for determining required channel clearances, either horizontal or vertical. Each has limitations. Tables 1 and 2 briefly reflect my personal views on the main strengths and limitations of each of the methods discussed above for horizontal and vertical clearances.

I hope that these comments fairly reflect the problems of a ship operator when assessing how wide and how deep a harbor entrance must be for a particular vessel.

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TABLE 1 - STRENGTHS/LIMITATIONS OF METHODS FOR ESTIMATING MINIMUM BANK CLEARANCE IN HARBOR ENTRANCE

METHOD	STRENGTHS	LIMITATIONS
EXPERIENCE TRANSFER Specific Situations	Direct evidence without modeling or calculating for very similar situations.	Not helpful for extrapolation to different situations or to great changes of scale.
Design Guidelines, e.g., PIANC, COE, TERMPOL	Represent distillations of quantities of experience.	Do not address local peculiarities, and tend to be conservative for design purposes.
HYDRAULIC MODELS	Good representation of bank and bottom irregularities and low speed ship control transients.	Very high cost and time requirements. Some model-ship scale effects in hydrodynamics and human control areas.
REAL-TIME SHIPHANDLING SIMULATORS With Outside View	Good representation of human control responses including variations. Conditions easily changed.	High cost and time requirements. Math models not yet validated for irregular bottom, banks, and current effects.
Without Outside View	Account for human control responses including variations. Conditions easily changed. Moderate cost.	As above regarding math models. Also, adequacy of human control responses has yet to be validated.
FAST-TIME SHIPHANDLING SIMULATION	Inexpensive, and allows great flexibility in studying effects of changes of problem parameters.	As above regarding math models. In addition, math modelling of human responses has yet to be validated.
DIRECT CALCULATION (e.g., Maximum Variation Method)	Inexpensive and quick for simple leading-line type of problem.	Not applicable to irregular bottom or bank, or to maneuvers with large transients.

TABLE 2 - STRENGTHS/LIMITATIONS OF METHODS FOR ESTIMATING REQUIRED STATIC BOTTOM CLEARANCE IN HARBOR ENTRANCE

METHOD	STRENGTHS	LIMITATIONS
LOCAL EXPERIENCE	Direct evidence, once fully acquired.	Takes time to develop for a new port, and can be costly if early estimates are inadequate or over-conservative.
TRADITIONAL ALGEBRAIC SUM OF ALLOWANCES	Errs on safe side. Also, allows some relative comparison from port to port.	Overconservative. Assumes all maximum values occur simultaneously.
STATISTICAL SUM OF ALLOWANCES	Realistically combines allowances.	Requires sufficient data for statistical summation of uncertainties of all factors. Presently limited regarding shallow water wave spectra and response amplitude operators for various ship types.

DISCUSSION

SEARLE: You have all the makings of a systems design, but it has become apparent to me over many years of casualties that you aren't playing the other part of the systems design game, and that is, the modes of failure, or hazards analysis. Now, the pilots know what I am talking about. The pilots will very quickly realize or come to learn in the Houston Ship Channel, for instance, two ships must not pass on such and such a bend. The National Transportation Safety Board begins to analyze accidents, and they notify the Coast Guard to tell the pilots that they shouldn't pass there, but the people who designed the port, the channel, didn't put a note on the plan that says ships should not pass on that bend. They did not do the failure mode and effects analysis or the hazards analysis. They didn't do that part of the systems design that deals with "what if."

I ask the question, do you rebut what I say, or do you, in fact, do that part of the systems design?

CRANE: This is certainly an important contribution to an integrated analysis--the knowledge gained by professional salvors and accident investigations. While it is included in a tacit way, I believe the rigorous kinds of analysis you mention would yield information in explicit ways that would lead to improved design and practices.

EVALUATION OF THE SAFETY OF SHIP NAVIGATION IN HARBORS

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Abstract

Concern for safety of navigation in harbor waterways has increased due to the huge economic and environmental consequences of potential accidents to those ships of rapidly escalating size operated or proposed for operation in harbors today. The authors describe a methodology for the determination of ship and waterway navigational safety, including the definition of measurement indices of safe navigation and the means for determining their values. This methodology is the result of extensive research sponsored by the Maritime Administration and the U.S. Coast Guard involving the study of navigation of ships in harbor waterways through real-time simulators.

Ship operators, port authorities, and regulatory agencies can apply the methodology to establish port and waterway designs or to evaluate the safety of accommodating potential traffic. The methodology is applicable to evaluation of limiting environmental conditions (i.e., visibility, wind, current) beyond which piloting of certain ship types can be considered unsafe, and examination of the effects of alternative aids to navigation, redesign of channels and turns, new traffic policies, or less-maneuverable ships.

Specific applications of the methodology and measures of safety to changes in ship controllability, turn design, and aids to navigation are included. An analysis of the channel characteristics of 32 U.S. harbors (i.e., channel widths, depths, turn angles, turn types) is included to serve as reference material for future U.S. ship designs.

Introduction

The advent of large ships carrying cargo harmful to the environment and the economic advantage of accommodating oversized vessels in existing ports has focused the attention of the public, port authorities, ship operators, and government agencies on the need for improvements in the safety of navigation in U.S. port waterways. To date, navigational safety in U.S. port waterways has been maintained at

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*Presenter.

a relatively high level by virtue of an evolutionary process. Ship size increased at a slow enough pace that channel requirements, aid to navigation requirements, and ship maneuverability requirements could be determined by trial and error. Given a number of near misses and an occasional accident, port and ship designs were improved to acceptable levels of safety. As one port showed its capability to accommodate particular vessels, another port sought the same type of traffic by improving its own design to be equivalent to the first. Out of this experience and limited research, rules of thumb and empirically derived design criteria evolved for channel dimensions, aids to navigation, and ship design.

Our difficulty today arises from the rapid escalation in ship size and the potential outdating of the available design criteria. An analysis of shipping traffic in U.S. port waterways would show that by many existing design policies and standards, present waterways cannot safely accommodate many of the large ships using the waterway today, much less the larger vessels of the future. Are present operations of oversized vessels safe or are we in a time-bomb situation? What is the present margin of safety for navigating large ships in existing channels? What economical improvements can be made to increase the margin of safety?

Clearly, analytical techniques need to be developed for quantitative evaluation of the navigational safety of narrow waterways for large ships. The evolutionary process is too slow to provide the criteria in a timely fashion and the environmental, economic, and social consequences of a major marine accident are too high to risk.

Statement of the Problem

Research conducted in the area of navigation of ships in narrow waterways was for many years focused on hydraulic channel testing and simulation of ships' hydrodynamic response in analog or digital computer models. These methods were used to evaluate a single transit of a channel by a ship. Typically, autopilot rudder and propulsion control algorithms were used to control the model or the simulation. The advantages of such research methods were repeatability, and the ability to isolate and study unique hydrodynamic responses. These research methods provided valuable data about the vessel's physical response in the waterway. The extent to which these vessels could safely transit the waterway, however, could not be ascertained, since these methods failed to acount for the variability the pilot and helmsman introduce.

Recognizing this deficiency during the past decade, several research institutions around the world have integrated the human element into research through the use of ship simulators. By considering the variability man's performance adds to the piloting process, we are truly considering the ultimate safety of the vessel in the waterway, for a waterway can be said to be safe to the extent that variability of ship tracks in the waterway can be contained within the boundaries of the waterway under stated environmental conditions.

The variability under study is that normally resulting from differences in perceptual and cognitive behavior between different pilots and helmsmen, and differences in behavior over time or for unique ships or channels for an individual pilot or helmsman. Research in this area must therefore be conducted to assure that a representative sample of subjects has been analyzed, in order to achieve a level of statistical significance transferable to the real world. The research methodology and examples presented in this paper appear to achieve these goals.

Methodology

The process for determining the requirements for safe navigation in restricted waterways was developed to address the following critical design and operational questions facing ship operators, port authorities, and regulatory agencies.

- Which environmental conditions preclude safe navigation in the waterways?
- Which operational procedures for specific ship types enhance their safe navigation in the waterway?
- What level of safe navigation is provided by the aid-to-navigation system in the waterway, or what is the effect of alternative aids to navigation?
- What maneuvering characteristics are required for proposed ships to navigate the waterway safely?
- Is the level of safe navigation acceptable for a proposed ship type in a given waterway, or what changes in the waterway dimensions are required to ensure acceptable safety levels?

All these questions must be addressed using methods that recognize it is performance of a human pilot exercising his capabilities in navigation that must be analyzed. Safely navigating a ship which is large for the channel is relatively routine for an experienced pilot if the ship is maneuverable and directionally stable, and there is no wind, current, or other perturbing influences, such as banks or traffic. Determination of safety, given an adverse environment with allowance for the variability in response by the pilot, is the objective.

The basic methodology consists of the following steps:

1. Define the characteristics of the harbor and its environment.
2. Define the operational characteristics of the ship.
3. Explore the interaction of the ship and the harbor in the presence of environmental conditions that limit a human operator's control of the ship during simulated harbor transits.
4. Analyze the results of that interaction through appropriate measures of safe navigation performance.

The elements of these four steps are discussed in subsequent sections of this report.

Step 1. Define Characteristics of the Harbor and its Environment

Many categories of information are required to describe a port sufficiently for a comprehensive study of safe navigation. The sources of the required data, however, are few, consisting of 1) navigation charts, light lists, and current direction and velocity data for the harbor published by the National Ocean Survey, and 2) weather information and statistics for the area published by the National Weather Service. Information collected from these sources should be compared with and enhanced by interviews with mariners and weather observers who have extensive local knowledge. The categories of data required for a port study include the following:

Waterway configuration
- Channel widths and depths
- Turn types and angles
- Bank and shoal locations
- Type and location of hazards

Environmental statistics
- Wind direction and velocity
- Current direction and velocity
- Visibility range
- Unique current conditions

Aids-to-navigation system
- Types of aids
- Characteristics and patterns (day and night)
- Location of aids

Operational policies and conditions
- Traffic rules and congestion
- Tug availability and size
- Limits on operations
- Types of vessels accommodated

The foremost limiting condition to large ships has generally been channel width and depth. To assess the general limitations of U.S. ports and waterways, the authors have developed a data base, resident in a computer file, which contains data on the physical channel characteristics of 32 major ports of the United States. Each straight channel leg and each turn in these harbors has been examined, and data on depth, width, aids to navigation, turn angle, etc., recorded. To assist naval architects contemplating design of future vessels, summary tables that characterize ports of the United States have been assembled from this data. These tables and the list of ports used are provided in Appendix A of this paper.

Step 2. Define Operational Characteristics of the Ship

Each question of safe navigation in a waterway implies a potential ship or family of ships. Normally, the problem involves the extension of the operating limits of the channel to allow passage of a larger ship or a ship of specific characteristics. It may involve guiding ships through a channel that has been restricted by, say, channel-side construction, or extension of port operational environmental limits to increase possible port use. In each case, a required component in the study is a mathematical hydrodynamic model of ship motion with the proper set of response coefficients for the ship's propulsion and control forces. Mathematical models of ship's motion have progressed to a stage at which there are a number of ship types available as models. Additionally, hydraulic model tests can produce good estimates for models' coefficients, given the ship's physical characteristics. Today's mathematical models include factors such as bank influence, shallow-water effects, bow thruster and tug boat forces, passing ship effects, and wind and current effects.

Step 3. Simulation of Waterway Transits Under Operator Control

The objective of the simulation is to determine how consistently, given the environment (ship characteristics, channel design, aids to navigation and possibly external help from tugs), a pilot operating with a helmsman can navigate the ship through the channel safely. An appropriate simulator facility which can address this problem is the full-scale ship simulator. The ship simulator normally consists of a full-scale ship's bridge with all normal equipment. Typically, there is a method for representing the visual outside world, the radar image of the world, and the progress of the ship through that world. The motion of the ship through the world is driven by the computer, using the hydrodynamic model, which is in turn driven by signals from the steering stand and throttle on the bridge. The technology of ship simulators has been most advanced in the Computer Aided Operations Research Facility (CAORF) which is located at the Kings Point Merchant Marine Academy and is sponsored by the National Maritime Research Center of the Maritime Administration. At CAORF, a 125-foot cylindrical screen extending for 120 degress to each side of the bridge portrays a computer-generated visual scene containing ships, shorelines, navigational aids, bridges, and buildings, realistically shown and moving in real-time response to the ship's movement. The visual scene can realistically simulate any level of visibility (fog) under night or day conditions. The visual scene is projected on the screen by special television projectors. The radar image is generated by a computerized radar signal synthesizer and is programmed to coincide with the visual scene. Pilots and masters navigating the ship experience the equivalent sensations and use the same information from the visual scene, the radar, and from the instruments as when navigating in the real world. CAORF has proved to be a valid, valuable tool for studying navigation performance with "man in the loop." CAORF

has been used to study many port design problems, including those of Valdez, Alaska;[1] Puget Scund;[2] Point Conception, California;[3] Galveston, Texas;[4] Pascagoula, Mississippi;[5] and the Santa Barbara Channel.[6] A multiyear research program has been maintained to systematically address a study of safe navigation in restricted waterways.

Step 4. Analysis of Simulation Results and Measures of Safety

To obtain the benefits sought in the methodology, performance measures must be defined that relate simulation results to safety. The objective of navigation in restricted waterways is primarily to maintain the position of the ship in the proper location relative to the channel boundaries or the channel centerline (i.e., establishing a proper crosstrack position). In the absence of traffic, the normal crosstrack position in straight channel legs is near the centerline. When meeting other ships, this position will shift toward the starboard boundary of the channel. The performance to be measured is the consistency with which pilots passing through the channel can determine and control their crosstrack position, recognizing the necessity for tighter consistency near the channel boundaries than near the centerline. As will be discussed, measures of safety are principally descriptive of crosstrack variation.

Along-track position in restricted waterways is of minor importance, except in two instances. The first instance is the determination of the position to begin a turn, after which negotiation of the turn again becomes primarily a crosstrack and turn-rate control problem. The second instance is bringing the ship to a stop at some location.

Measures of navigation performance in restricted waterways are therefore directed to measuring consistency of crosstrack position for repeated transits of the channel by many pilots under the same conditions. Changes in safety of navigation are defined by determining differences in the measures for changed conditions. Three principal measures have been derived and effectively applied across various experimental conditions.

1. The mean track location across the channel of the:
   - Ship's center of gravity (CG),
   - Port and starboard extreme points of the ship's hull.
2. Statistical limits descriptive of the variability about the mean track:
   - Standard deviation of crosstrack locations at points along the track,
   - Location of the 95 percent limit of the track envelope of the CG.
3. Combined index.

Measures 1 and 2 may be easily understood by considering the plot of these data along a sample channel. Figure 1 shows these data

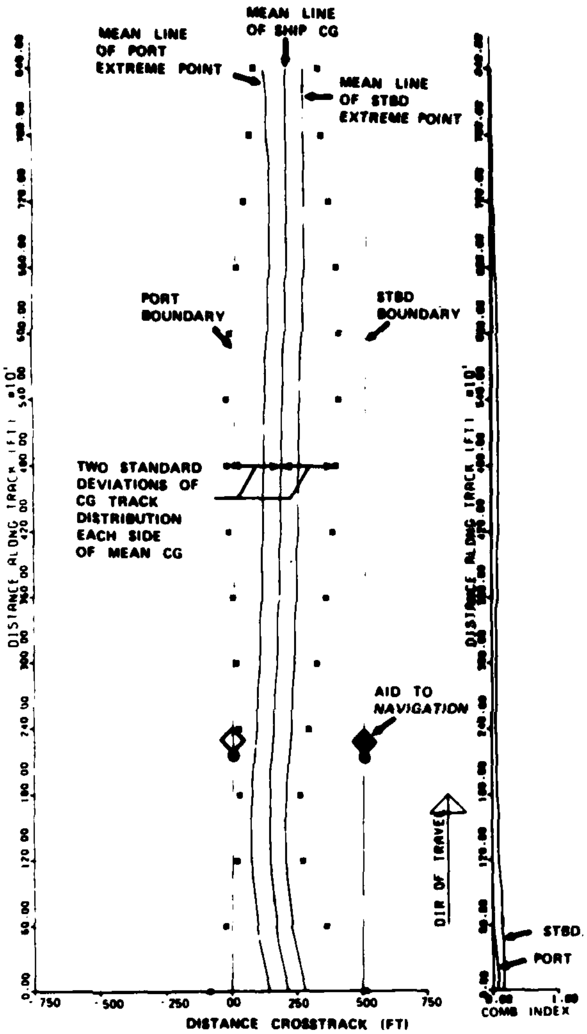

Figure 1. Plotted measurement of performance.

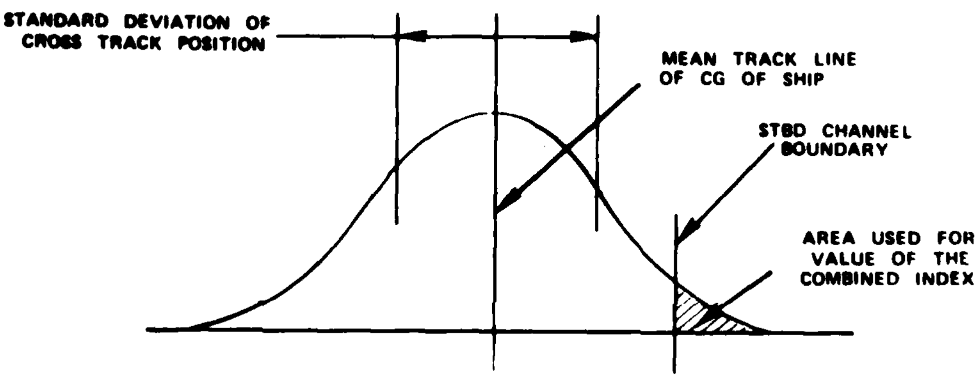

Figure 2. Combined index.

plotted at 600-foot increments along a channel. The dashed lines indicate the channel edges, and solid lines indicate the mean tracks of the ship's CG and the port and starboard extreme points. The square symbols show the CG standard deviation doubled on either side of the CG mean point. If the distributions of crosstrack variance are assumed to be normal, this envelope would contain 95 percent of all transits.

Measure 3 is called the combined index because it combines the mean ship position in the channel and the variation of the transits about that mean position. This combination has desirable features for predicting navigational safety in restricted channels. Neither the mean ship position across channel nor transit path variability alone give a complete description of safety. When combined in one index, however, the index can discriminate between tolerance for higher path variability when the mean track is far from the channel edge and the requirement for low track variability when the mean track is near the channel edge or when passing another ship, and assign both conditions a favorable value.

The index computation is shown graphically in Figure 2. A normal distribution based on the standard deviation of the center of gravity point is centered on the mean crosstrack position of the CG point. The index value is the integrated area under the distribution curve which lies beyond the channel edge. The values of the combined index are plotted on the right side of Figure 1.

The two curves are for the values relative to the port boundary (P) and starboard boundary (S). Insufficient data are available to test if the assumption of normality is correct. In fact, it is suspected that a truncated distribution may be more characteristic of the crosstrack variance as the edge is approached. The assumption of normality, however, is conservative, and sensitive to changes in pilots' performance. Since it is not necessarily the proper distribution, the index should not be interpreted as a probability of grounding.

The values for the combined index included in this paper have been calculated relative to the mean ship center-of-gravity location. The process can easily be applied to calculate values relative to the mean port and starboard extreme point locations at along-channel locations. The index values for the starboard extreme point would be relative to the starboard channel boundary only, and the values for the port extreme point index would be relative to the port channel boundary only. The resulting index would reflect mean channel position, track variance, and heading error.

Application of the Methodology to Port Design Problems: An Overview of Findings

The Maritime Administration has conducted a series of experiments with their CAORF facility to evaluate the performance of navigation in restricted waterways. These experiments have investigated those areas of performance in which the master's, the pilot's, or the docking master's variability is likely to cause the ship to exceed safe operating conditions. The experiments have provided an initial

understanding of the complex and interdependent relationships of harbor design parameters. They have uncovered a number of mitigating measures that can be applied in specific problem areas to achieve satisfactory performance in heretofore marginal situations.

Six harbor design issues have been addressed at CAORF. These are: channel dimensions, environmental limits, operating procedures, tug requirements, aid-to-navigation requirements, and ship maneuvering requirements. The influence of each of these issues on the variability of masters, pilots, or docking masters is described briefly in subsequent sections. Specific data are not quoted in these sections, due to the large number of experiments from which conclusions were derived and the difficulty of comparing findings from specific experiments. Examples of performance measurement in several of the areas are presented separately in a succeeding section ("Examples of Analysis...").

Channel Dimensions

The adequacy of channel dimensions has been addressed in several harbor design experiments. Most recently, studies have been concluded on the Galveston ship channel, the Restricted Waterway Experiments IIIA (8), and IIIB (9), and the Pascagoula ship channel. Experiments in channel dimensions generally addressed channel width, turn configuration, or both. Typically, worst-case wind and current combinations were selected. Experimental conditions tested whether subject pilots could safely maneuver in the proposed channel under the selected conditions.

As a result of the wind and current variability and the requirement for the pilot to maintain a high drift angle against the wind and current, a ship's tracks displayed a high level of variability in crosstrack position both within runs and between runs. Although this variability does not show a large dependence on channel width, the channel width must contain it and allow for an additional margin of safety.

Depending on the turn design (effective maneuvering radius allowed), the crosstrack variance in some cases was significantly affected when exiting the turn: the smaller the required turning radius, the higher the crosstrack variance during and exiting the turn. Analysis of performance in turns has indicated pilot control actions are initiated in anticipation of the turn. For small-radius and narrow turns, the pilot's anticipated actions must be accurate in magnitude and precisely timed. For large-radius turns, there is more room for error in the anticipatory actions, and for making corrective actions during the turn. Proper turn design has been shown to reduce crosstrack variation in a narrow waterway.

Environmental Limits

The selection of appropriate wind and current conditions, and even the limits of visibility, is an important issue in any harbor design study. Typically, a ship operator or port authority specifies limits below which he requires 100 percent operation. Limits are defined by the frequency and distribution of local weather conditions and the economic consequences of occasional delays in delivery or shipment. In studies where the port is to be open to many operators (e.g., Galveston), environmental conditions are selected to provide, for example, 90 to 95 percent harbor availability based on weather and current statistics.

The effect of environmental conditions on the ship and pilot are twofold. First, the ship must "crab" along the channel with a specific drift angle to maintain a ship's course equivalent to the channel course. Second, due to the presence of high drift angles, the pilot's perception of his position, and therefore the accuracy of corrective orders is degraded. Drift angle increases the "swept width" of the ship's path, thus occupying a wider portion of the channel. The effect of the degradation of the pilot's control process is to increase the crosstrack variability. The net effect of environmental conditions is thus seen to be a reduction in safety, placing the extreme points of the ship closer to the channel edges and increasing the crosstrack variability of those points.

Current and wind combinations may also degrade performance in turns. Typically, the most severe effect evolves from a following current when the ship's ground speed appears high while the water speed is low, impairing maneuverability. Excessive windage can contribute to difficulties in turning depending on the topsides and superstructure configuration. In cases where environmental conditions degraded turn performance, crosstrack variation exiting the turn was high, and the only solution appeared to be widening the channel following the turn.

Operating Procedures

Many design studies involve handling ships in new harbors or modified waterways. Until recently, there was little experience in the United States with oversized vessels (e.g., 150,000 DWT tankers and above). Most harbor design studies of today, however, involve accommodating such vessels in U.S. ports.

With increased environmental pressures, authorities must consider establishing operational limits, be they environmental (wind strength, current cycle, etc.) or procedural (specified routes, speed, traffic conditions, etc.). Procedures also need to be established that could act as mitigating measures to ship system failures. Several port studies at CAORF have addressed these issues: the Valdez tanker study, Puget Sound speed limit study, and Point Conception LNG* study.

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*Liquefied natural gas.

The issue of many procedural studies is to determine the safest approach and departure routes to a harbor across the environmental conditions. In Valdez, the departure route proved to be the design issue. By reducing a turn angle along the route, crosstrack variance passing by a middle rock was reduced. For the Point Conception operations, the evaluation of the approach route concluded that crossing an oncoming traffic lane would present little hazard.

The findings of several port-related studies have indicated that safety may be inversely dependent on ship's speed over a limited range. The first impression is that slow ship speeds will be inherently safer. Data indicate, however, that with reduced speed comes a reduction of maneuverability and an increase in crosstrack variability. Increased speed not only increases maneuverability, but also significantly reduces the required drift angle for adverse wind and current conditions.

Tug Assistance

Harbors planned for accommodation of oversized vessels often assume the use of larger shiphandling tugs than are generally available in U.S. ports today. Several port design experiments at CAORF have addressed the use and size of tugs for oversized vessel operations. Notable are the Point Conception Study, the Galveston Channel Study and the Pascagoula Channel Study.

The use of tugs as rudders, and for slowing vessels by means of long lines astern, is frequently practiced in Europe and Japan for oversized vessels, but has not yet received much attention in the United States. The interdependence of tug power and ship type and size with environmental conditions is important, but is yet largely unknown. A high-fidelity simulation of tug forces has been recently added to CAORF and will be applied in a number of experiments in the near future.

Aids to Navigation

Visual aids to navigation appear to serve as a mitigating factor to some of the perturbing environmental and channel design variables. Providing extra aids in a channel has resulted in lower crosstrack variance and improved performance in difficult turns. Experimental conditions with fewer aids resulted in higher variance and unacceptable performance in channels of equivalent design and environmental conditions. Deficiencies in some harbor waterways might thus be overcome with additional aids to navigation.

Evaluation of precise radio aid navigating systems has been undertaken to evaluate potential performance gains achievable through a highly accurate positioning system. Data gathered so far indicate excellent trackkeeping performance. Just as visual aids to navigation, advanced radio aid systems may be employed to overcome marginal operating conditions in ports in place of port modifications, such as widening channels.

Ship Performance

The effects of ship controllability on variability of trackkeeping has suggested that newly constructed ships might be custom-designed for a specific port or type of waterway. LNG operations are particularly suitable for this type of investigation due to the ships' commitments to certain terminals.

An experiment conducted at CAORF indicated that track variability increased with a reduction in the turning response of a large tanker. Improvements in maneuverability of large vessels using advanced design concepts may prove highly beneficial to safe navigation in restricted waters. Of interest is rudder size, number of rudders, number of propellers and perhaps hull form. If higher turning moments could be produced at low speed (e.g., twin screws), perhaps safe operations could be conducted at very low speeds. This area of performance is still at the basic research level, but the gains to be achieved are promising.

Examples of Analysis of Relative Navigational Safety in Narrow Waterways

Specific comparisons of navigation performance evaluation for alternative ship characteristics, channel design, and aids to navigation have been drawn from two recent experiments at CAORF. During these experiments, Restricted Waterways Experiment Phase IIIA and IIIB, trained pilots navigated an 80,000 DWT tanker along a 500-foot-wide channel containing three turns connected by straight channel segments. This channel configuration is shown in Figure 3. Five pilots made transits through the channel for each variation in a specific condition, providing a statistical basis for evaluating the relative effect(s) of the condition on safe navigation. Results for these experiments have been reported in references 8 and 9. For this paper, several experimental conditions have been selected to illustrate the value of analysis of navigation safety using the measures previously described.

Ship Maneuverability

The amount of control force required to enable ships to negotiate waterways is one factor to be considered in the design of a new ship. There has been a feeling among mariners that given enough training and experience, man is sufficiently adaptable to overcome difficulties with slow-responding ships. The purpose of this comparison was to determine, in relatively severe environmental conditions, what actual effect a reduction of maneuverability would have on safe navigation of a ship in restricted waterways. Would the pilots compensate for the slow response or would overall safety be reduced?

For this experiment, the ship was modeled with two alternative rudders. One rudder was the standard rudder used for an 80,000 DWT

tanker. The alternative rudder had only one-half the effective area of a standard rudder. The results should be of interest to naval architects as well as port authorities and ship operators.

The channel transits through the first leg, first turn, and second leg of the channel shown in Figure 3 were compared. The first leg required compensation for a crosscurrent, while the second leg had a following current. Graphic presentation of the results is shown in Figures 4, 5, and 6.

The results show that the pilot was not able to compensate fully for the reduced maneuverability. Transits with the less-maneuverable ship resulted in greater variability in track position in the straight legs and turns, as illustrated by the crosstrack standard deviations. The mean track line is more sinuous on both straight legs for the less-maneuverable ship. The mean extreme point violates the channel boundaries in the first leg, as illustrated in Figures 4 and 6. The combined index values averaged along each segment are given in Table 1. In all instances, the more highly maneuverable ship allowed smaller combined index numbers. There is clear indication that with less-maneuverable ships, pilots require more channel width for safe navigation.

Turn Configuration

Turns in channels of the United States are generally of two types, non-cutoff turns and cutoff turns. The basic difference in the two types is that the vertex of the channel boundaries on the inside of the turn has been cut back on the cutoff turn, while it has been left intact on the non-cutoff turn, Figure 7. The two types of turns are about equally common.

Navigation through 30-degree cutoff and non-cutoff turns were investigated during the CAORF experiments. Graphic display of the results for turns is shown in Figure 8. Experienced pilots navigated cutoff turns more smoothly and safely than the non-cutoff type. Their mean cross-channel position through cutoff turns was close to ideal, while the combined index values are uniformly negligible. On non-cutoff turns, the pilots entered the turns and exited the turns wider and with greater variance in track line position. There is a focal point on non-cutoff turns at the turn apex at which the track variance is very low. The pilots apparently must pass through this point on the turn regardless of their position entering the turn and without regard for the effect on turn recovery. This effect is not apparent on cutoff turns where the pilots can establish a smooth curve through the turn and continue the line through recovery entering the next channel with a low crosstrack standard deviation. A rather dramatic reduction in the average combined index for the cutoff turn may be noted in Table 2.

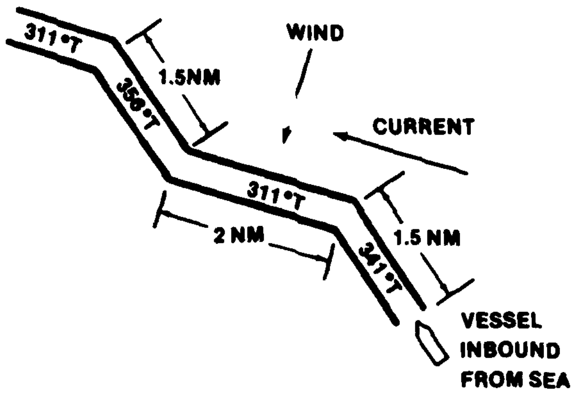

Figure 3. Characteristics of experimental channel.

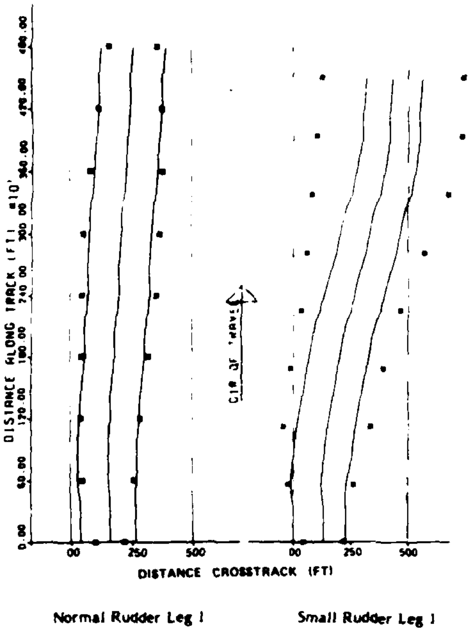

Figure 4. Effect of rudder size in Leg 1.

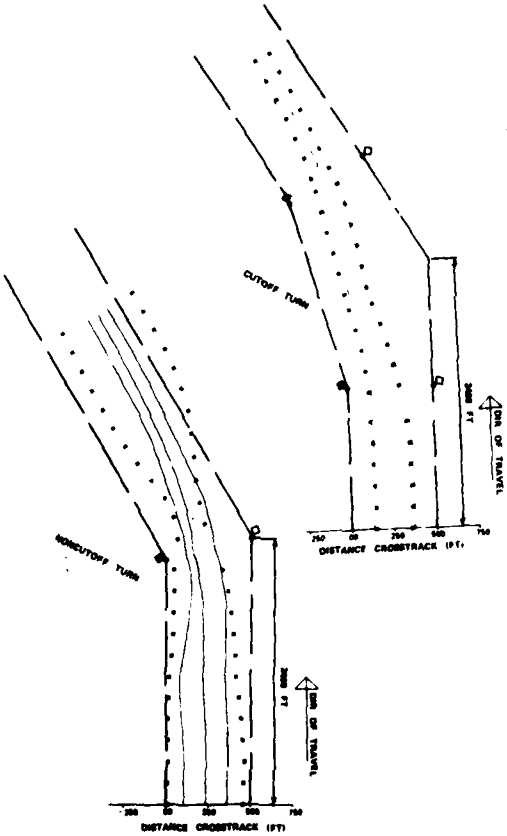

Figure 5. Effect of rudder size in turn.

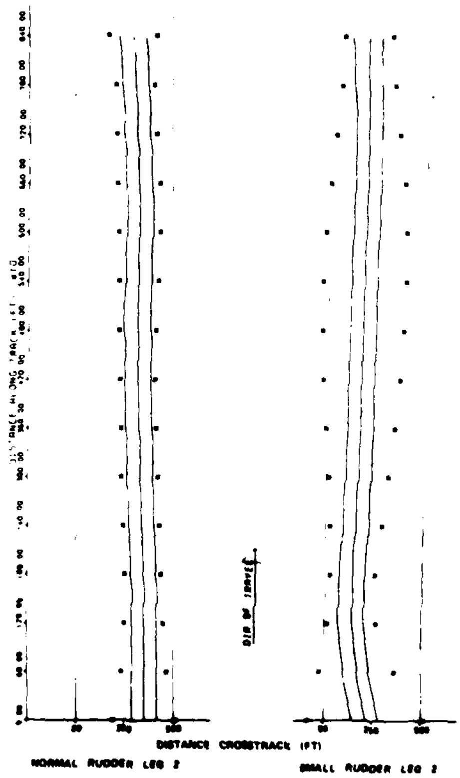

Figure 6. Effect of rudder size in Leg 2.

TABLE 1. AVERAGE COMBINED INDEX COMPARISON FOR NORMAL AND SMALL RUDDER SHIP

Average Combined Index

	Leg One Cross Current		Turn		Leg Two Following Current	
	Port	STBD	Port	STBD	Port	STBD
Normal Rudder	.151	.014	.085	.009	.029	.001
Small Rudder	.233	.260	.114	.226	.085	.011

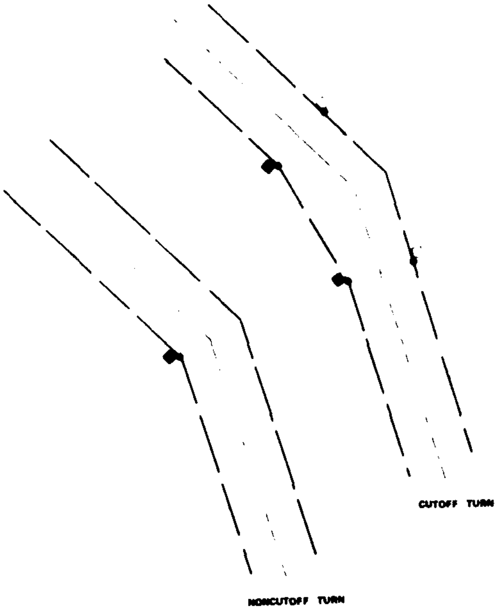

Figure 7. Cutoff and non-cutoff turns.

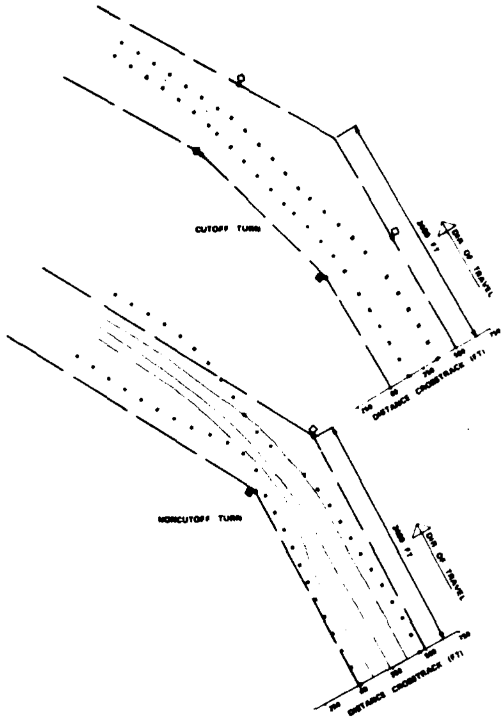

Figure 8. Effects of types of turns.

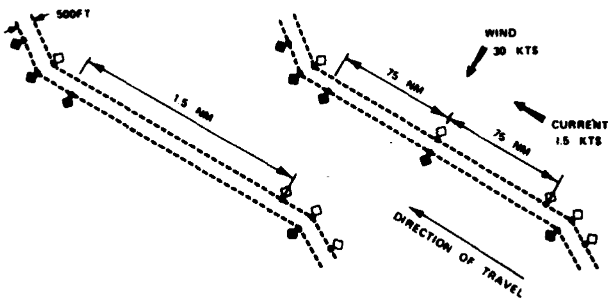

Figure 9. Experimental channels with and without midleg buoys.

TABLE 2. EFFECT OF TURN CONFIGURATION ON COMBINED INDEX

Turn Condition	Average Combined Index	
	Port	Starboard
Noncutoff Turn with Corner Buoys (Small Radius)	0.056	0.032
Cutoff Turn with Gated Buoys (Larger Radius)	0.003	0.001

TABLE 3. EFFECT OF ADDING MIDLEG BUOY

	AVERAGE COMBINED INDEX			
	WITHOUT GATE		WITH ADDITIONAL GATE	
	PORT	STBD	PORT	STBD
Without traffic	0.000	0.276	0.000	0.004

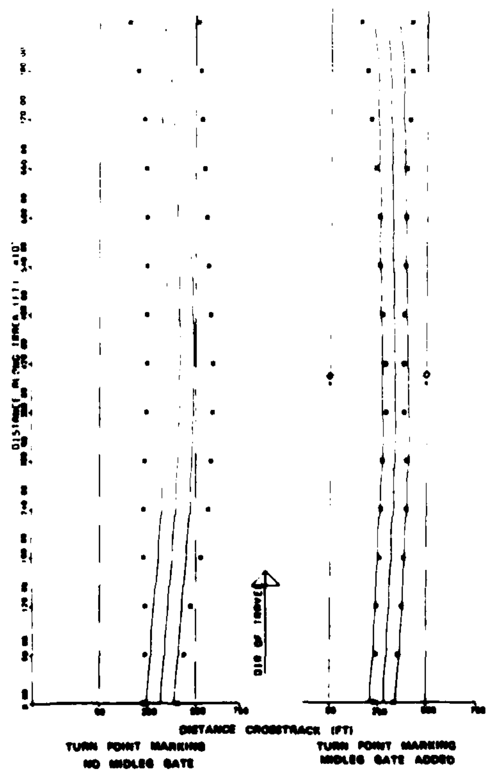

Figure 10. Effect of adding midleg buoys on straight legs.

Additional Channel Markings

Many channels consist of a series of relatively short (1.5 to 1.7 nm) straight legs separated by turns. The turns must be marked so their position is known. It has not been clear, however, that the addition of buoys along the straight legs away from the turns is cost-effective with regard to increased safety. During the CAORF experiments, the second leg of the channel provided an excellent comparison of the effect of turn markings only versus the addition of a gated pair of buoys midway along the leg. The two configurations are shown in Figure 9.

The results are presented graphically in Figure 10. The average combined index values are shown in Table 3.

Conclusions from this comparison are that the additional buoys clearly caused the mean track line to shift toward the center of the channel away from the edges and reduced the variance between transits. The combination of improved mean track line position and lower track line variance reduced the combined index values to essentially zero. As shown in Figure 10, these results clearly illustrate the potential use of aids to navigation to reduce crosstrack variance in certain channels and to increase the relative safety margin by holding the mean track near the channel centerline.

Conclusions

Performance data gathered from experiments with the ship simulator at CAORF have shown that a number of port design parameters directly affect piloting variability and navigation safety in narrow channels. The safe operational configuration of any port can be seen to be an appropriate combination of channel dimensions, operating procedures, limiting environmental conditions, ship maneuvering characteristics, and aids to navigation. Such combinations must yield a variability in trackkeeping performance that will fall safely within the defined channel for multiple ship transits. In this context, the design of any particular port is seen to be unique, each of the factors listed above providing specific limitations on the design parameters. The evolving experimental data base in port design from CAORF is increasing our understanding of the complex relation of piloting variability to safety and port design parameters. Using the methodology and experimental analysis developed at CAORF, we are now able to find mitigating solutions to many cases of identified problems that are cost-effective and that may have minimal environmental effects.

The effectiveness of the present methodology is demonstrated by its ability to sense changes in all critical port design parameters. The formulated performance measures are effective in addressing the following requirements:

- Summarizing along-track performance;
- Identifying specific problem locations and reflecting changes required to solve them;

- Providing numerical indices for comparison of relative safety.

The final requirements of these measures will be to provide absolute indication of safety relative to actual behavior at sea. Measures indicative of the actual probability of grounding per transit will be sought over the next several years through extended experimentation at CAORF and at-sea data collection.

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Appendix: The Physical Characteristics of Waterways in 32 Major Ports

Information covering physical characteristics and present aids to navigation of 32 major U.S. ports has been collected and entered into a computer data file. The ports selected and their regions are listed in Table 4.

Using the most recent U.S. Coast Guard navigational charts, data descriptive of the physical dimensions of channel segments in each port were documented for each of the following four categories:

TABLE 4. COASTAL REGIONS AND PORTS EVALUATION IN THE DATA BASE

East Coast	West Coast
Portland (ME)	Long Beach
Boston	Los Angeles
Providence	San Francisco
New London	Portland (ORE)
New Haven	Seattle
New York	Juneau
Albany	Valdez
Philadelphia	Honolulu
Baltimore	Coos Bay
Chesapeake Bay	
Norfolk	**Gulf Coast**
Wilmington (NC)	
Charleston (SC)	Tampa
Savannah	Mobile
Jacksonville	New Orleans
Miami	Port Arthur
	Houston/Galveston
Great Lakes	
Duluth	

- Straight channel: the space between turns or larger areas of water that is delineated by dashed lines on navigation charts.
- Turn: a change in direction coming out of one straight channel and going into another.
- Bay: an open area of water with no dredged area or delineation of channels. Boundaries are land masses.
- River: as given on a chart. Boundaries are the river banks.

The physical data compiled were channel width, depth, length, turn angle, and turn type (dredged configuration). The remaining data were code numbers and chart numbers that allowed retrieval of data from the computer data base and cross-reference to charts.

When necessary, averaged widths of the rivers and bays were entered, and generally where there were different depths, the shallowest was chosen. Dashed lines delineating the channels on the charts were used as a basis for measurement. Depth is taken from the chart tabulation table or measured directly. Only channels with depths of 29 feet or deeper were considered for this analysis.

There were entries for 835 channel segments, of which 47 percent were straight channels, and 46 percent were turns. The remaining 7

percent were rivers and bends. Only the two larger groups by occurrence (straight channels and turns) have been tabulated.

Straight Channels

Straight channel depth and width for each port is given in Table 5. Figure 11 is a histogram that summarizes the number of channels by categories of width for all ports. It is apparent from the figure that the greatest number of straight channel segments are less than 600 feet in width and that the majority are either between 350 and 400 feet or between 550 and 600 feet.

The distribution of straight channel depths is shown in Table 5.

Turns

Distribution of depths and widths of turns parallel the findings for straight channels. Physical data common only to turns are the types of turn configurations and the angles of turns.

The determining factor of turn type (cutoff, non-cutoff, or bend) was delineation on the navigational charts. A series of cutoff turns with extremely short (less than 1/4 nm) straight channels connecting them was counted as one bend, regardless of delineation. Bends amounted to approximately 50 nm, mostly in the ports of Houston/Corpus Christi.

Figure 13 shows that of all turns sampled, more than 75 percent are 40 degrees or under, 34 percent are between 20 to 40 degrees, and another 43 percent are turns of 20 degrees or less. Of the 23 percent that are greater than 41 degrees, many represent turns on to a secondary channel.

DISCUSSION

JOHNSON: Does this apply to large bays and relatively shallow or dredged channels only, or does it also apply to approach channels, deep water, jettied entrances?

BERTSCHE: It can apply to either problem. There are data bases that give the entire bottom, and the effect of shallow water comes in automatically.

KNIERIM: The radius of the turn at several places in New York Harbor where there are several marks for different circles in the same turn, necessitates a different wheel. You have to increase the wheel to set the ship turning, then when you get in the middle of the turn, the arc flattens out and the radius becomes longer, and you have to ease your wheel, at times reverse wheel. At the end of the turn, you must increase the wheel sharply and get the ship swinging to stay on the course. Whenever possible, any turn, regardless of the degree

TABLE 5. SUMMARY OF STRAIGHT CHANNEL DEPTH AND WIDTH FOR EACH MAJOR U.S. PORT (DEPTH IN FEET)

	WIDTH				
HARBORS	350-400	400-500	500-600	600-800	800-1000
Portland					35
Boston	32				35
Providence	35		40		
New London			33		
New Haven	35	35			
New York	35	35	35	35	
Phildelphia		40		40	40
Albany	32	32	31		
Chesapeake		35		42,37	41,40
Baltimore	27			42	35
Charleston	35,33	35	35	35	35
Norfolk				42,40,45	45
Wilmington	38	40			
Savannah	38	40,38	40		
Jacksonville	30	38,39	34	42,38	
Miami		38,35			
Tampa	34,32	36	36		
Mobile	40	40	42,40	40	
New Orleans		36,33	40,30,38		
Port Arthur	40	40			
Corpus Christi		45	47,47		
Houston	40,35			42,40	40
Los Angeles		47			
Long Beach				60	
San Francisco	30	45,30,35	35,30		
Portland		40	40	40	
Coos Bay	30				
Seattle					55
Juneau					30
Honolulu	35	40			
Duluth					

of the turn, should have the same mark in the water and the same radius.

BERTSCHE: Yes, I would like to comment on that. In all my years of schooling, I really learned one thing in this area, and it became apparent as we looked at all the charts of all the ports to build a large statistical data base: all straightaways in the United States are connected by turns. The turn is such a perturbative factor that attention to turning phenomena and their accommodation, if it can be facilitated, enables consideration of more narrow dimensions.

SHIP CONTROLLABILITY

J.P. Hooft

Introduction

This discussion gives special attention to methods for taking ship controllability into account in designing a waterway.

In evaluating the merits of a waterway (harbor entrance or port), economic considerations will be based on the comparison between the costs (building and maintaining) and the benefits (amount of cargo to be transferred in the port). Both the costs and the benefits are influenced by (among many other factors) the navigability of the waterway.[1]

When determining the navigability of the waterway, the controllability of the ships is an integral part of a complicated system.[2/3] For this reason, attention is increasingly devoted nowadays to the controllability of ships as traffic densities increase, maneuvering properties change (owing to the increase in the sizes of ships), and more ships carry hazardous materials.

The controllability of ships is determined by the combination of the ship's maneuverability[4] and the actions of an appropriate man-machine control system.[5/6/7] In addition, one will find that for a given combination of ship and control systems, the controllability of the two-component system will change with environmental conditions (such as harbor configuration). For this reason, one should be more interested in the navigability of a waterway as determined by the effects of the total "ship-control-environment system" rather than in the maneuverability of the ships alone.

Reluctance to determine the navigability of a waterway, or even to determine the controllability of ships in a given waterway results from the fact that such determinations do not hold generally. For each type of maneuver (approach, stopping, docking) in each type of waterway (approach channel, canal, port or berthing area at sea), different solutions will be found.

Although the quantification of ship controllability will differ for each case to be considered, the method will always be based on operational research involving statistical descriptions of systems. The results of such studies provide the possibility of performing risk analysis.

Even in the face of the difficulties mentioned, it would be very beneficial to develop systematic information on the controllability of ships for various waterway configurations. This information would be most useful in establishing the preliminary design of the waterway. This preliminary design can then be evaluated and the design corrected and refined. This second attempt--consisting of one or two alternatives--will need a detailed study of navigational aspects,[8] taking into account the ship's controllability. These detailed studies are often performed by means of simulation techniques (in a model basin[9] or simulator[10]).

General Description

Throughout this paper, the term "ship" should be understood to denote "ship-control system." Separate consideration of the inherent characteristics of the ship in the dual system will be indicated by the term "maneuverability."

Since no uniform definition of ship controllability is presented in the literature, use is made here of the following description, illustrated in Figure 1: A ship is defined to be controllable when it can be handled in such a way that the deviation of the actual maneuver (described by all stated variables of the system) from the desired maneuver remains within pre-set limits.

The essence of the description lies in two items:

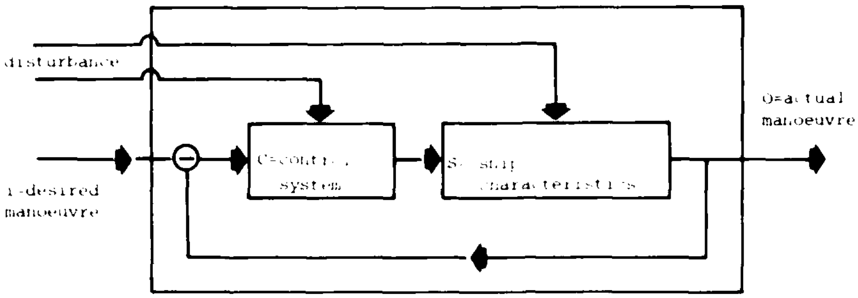
a. Knowledge of the discrepancy between the actual maneuver and the intended maneuver.
b. Knowledge of the preset limits indicating the acceptability of this discrepancy relative to the available space (domain available for the maneuver).

With respect to (a), it should be remembered that the ship's controllability will depend on the environmental conditions as they influence the actual maneuver. With respect to item (b), the environmental conditions influence the ship's controllability as they affect the degree of acceptability of certain risks.

This interaction between the influence of the ship's controllability on the requirements of the layout of a waterway, and the influence of the waterway configuration on the ship's controllability, necessitates complex definition and analysis of the navigability of a waterway.

The executed maneuver shown in Figure 2 brings out these points. Of the many possibilities, two will be discussed here.

1. Assume the preset limit reads: The controllability of the ship should be such that the ship will never hit the banks of the approach channel. The ship in this case is taken to be a tanker, and the banks are rocks. It now will be obvious that the maneuver actually performed deviates so much from the intended maneuver that the preset limit has been exceeded. The loss of control in this situation could have been caused by:



S - inherent ship characteristics ≙ ship's manoeuvrability

$\frac{O}{I}$ - behaviour of controlled ship ≙ ship's controllability

Figure 1. General description of the controlled ship by means of a block diagram.

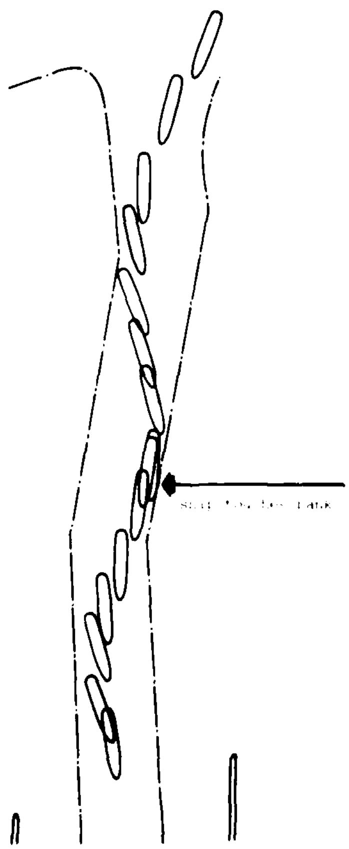


Figure 2: Manoeuvre performed with a simulated ship entering a harbour through a dredged channel.

a) Inadequate ship maneuverability,
b) Inability of the mariner to control the ship,
c) Malfunction of hardware elements in the steering system or the navigational aids,
d) Poor channel configuration, or
e) Unacceptable environmental conditions such as wind, waves, or currents.

2. Assume the preset limit reads: The controllability of the ship should be such that the banks will only be hit by a ship once in, for example, 10,000 passages through the channel. In this case, the channel bottom is muddy and the ships are dry cargo ships. It now will be obvious that the controllability of the ships passing the waterway is acceptable when the executed maneuver is a rare example of many maneuvers during which the banks have been cleared.

Since the ship's controllability depends on so many items, it might be of interest to ascertain a basic value of controllability for a given ship. This value is principally sought to serve as a reference. Such a reference value would represent controllability resulting in minimum deviation between actual and projected maneuvers, or in other words, the ship is optimally controllable when it performs maneuvers that show the closest agreement with the hypothetical maneuver designed for the waterway. In the paper by the SNAME H-10 panel,[11] the suggestion is offered that this reference value be defined as the "inherent controllability."

In addition to this suggestion, the following considerations might also be of interest. Returning to the description of ship's controllability, for the allowance of deviation of the actual maneuver from the intended, some area is required at each stage of the passage if many ships pass. This so-called width of lane can only be determined with some chance that the ships will pass within the area. According to the SNAME H-10 panel, this width of lane is determined by the piloted controllability of the ship. The reference (optimal) amount of piloted controllability is called "initial controllability," and can be defined as that amount of controllability for which the width of lane will be minimal for the situation considered, ignoring all types of disturbances.

To show the difference between this latter concept and the definition of the H-10 panel, the following observations can be made:

- Inherent controllability refers to the best abilities of the ship resulting from its maneuverability characteristics.
- Initial controllability refers to the best behavior of the ship resulting from the combined effect of "ship-controller-waterway" characteristics.
- For the evaluation of the navigability of a waterway, both considerations--"inherent controllability" and "initial controllability" (= best piloted controllability)--have to be considered to arrive at a most beneficial waterway design (minimal costs and risk of accidents).

A hypothetical example will be discussed in the next section to elucidate the analysis of ship's controllability in a particular waterway.

Considerations in Designing a Port

Starting Points of the Design

A harbor is to be designed alongside a coast for the docking of LNG carriers only of 125,000 m^3 or smaller. (The schematic plan for the design is illustrated in Figure 3.) The port is to accommodate the arrival of 136 ships per year over a period of 20 years (about 5500 passages in the harbor). In the approach channel, the ships sail through currents and waves, while the channel depth is designed for 15 percent keel clearance to the ship. The maximum current amounts to 3 knots while the ships sail in prevailing winds of either 5 Bft or 8 Bft.

The first decision to be made is the approach speed of the ships. Assuming a 2750 m length for inner and outer harbor--based on experience from earlier studies--it is stipulated that the ships will pass the outer piers at a speed of approximately 5 knots, with a maximum variation of 1 knot, while 4500 m in front of the outer piers their velocity is 8 knots.

The port design will also be based on the fact that the tugs will fasten inside the outer harbor region. Another shore-based decision for the design stipulates that only one ship at a time will approach and dock in the harbor.

At this stage, the question arises what the dimensions of the approach channel (to be dredged) and the distances between the piers should be. When "design charts" for the width of shipping lanes are available, a compromise can be attained for the optimum harbor mouth. This compromise would fall somewhere between as wide a harbor mouth as possible for navigational purposes and as small a harbor mouth as possible to minimize wave penetration into the harbor.

Exploring the waterway dimensions required to facilitate the entry of ships into the harbor, the inherent controllability will lead to a width of the approach channel dependent on the ship's drift angle against current and wind, while the dimensions of the harbor mouth and the area behind it will depend on the current shear in front of the outer piers.

Further exploration will show that the initial controllability of the (piloted) ship leads to the following design alternatives, assuming the ship approaches a channel 500 meters wide under conditions of no current, but some wind disturbance typical of normal operations.

Design Alternative A

- Available width of outer harbor mouth 500 m
- Required width of lane in the approach channel ~290 m
- Required width of lane between the outer piers ~240 m

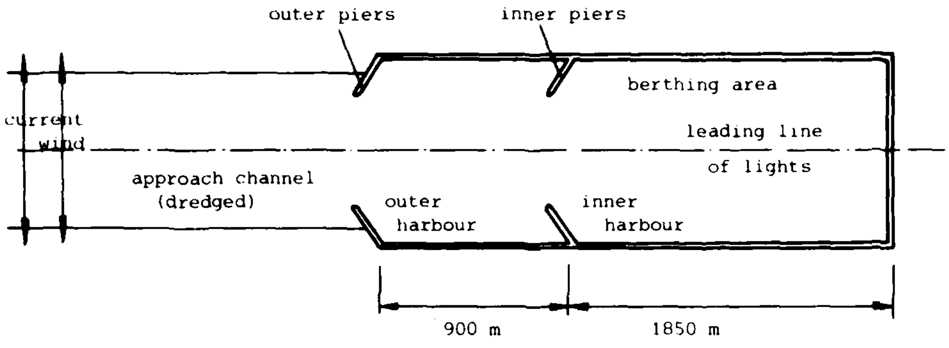


Figure 3. Schematic plan of the design.

- Required width of lane in the outer harbor ~230 m

Design Alternative B

- Available width of other harbor mouth 300 m
- Required width of lane in the approach channel ~600 m
- Required width of lane between the outer piers ~220 m
- Required width of lane in the outer harbor ~245 m

The results presented in Figures 4 and 5 have been reduced from the average value and standard deviation of many maneuvers of ships entering the harbor in the conditions specified. For the winds blowing from starboard, half the required width of lane is determined by the average and the standard deviation presented in Figure 6.

Assessment of Initial Controllability

Before comparing the two options to be developed, more attention is devoted to the theoretical meaning of the information provided. The question arises: are the required widths of lane in Figures 4 and 5 completely described by the initial controllability of 125,000 m^3 LNG carriers in the harbor considered?

This question can be answered affirmatively if all boundary conditions (ship speed, prevailing wind, etc.) mentioned in the starting points of the design are taken into account. This means that in the option of an outer entrance 300 meters wide, the ships' controllability is such that an approach channel at least 600 meters wide is required. The channel width has to be 600 meters "at least," because the initial controllability is considered to provide the minimum deviation between actual and intended maneuver. During normal operations, the ship's controllability will be less (leading to larger channel widths) than the initial controllability, as will be shown later.

The navigability of the waterway can only be improved when the starting points of the waterway design are changed or by reference to another ship system (maneuvering characteristics of the ship in the combination-of-control method). The controllability of the ship can be improved, for instance, by giving the pilots special training, by providing other aids to navigation to the pilots,[12/13] or by increasing the water depth, by which the turning ability of the ship increases.

Taking these additional considerations into account, it can be assumed that from a practical point of view, the results presented in Figures 4 and 5 represent the initial controllability of the 125,000 m^3 LNG carrier in the two alternatives.

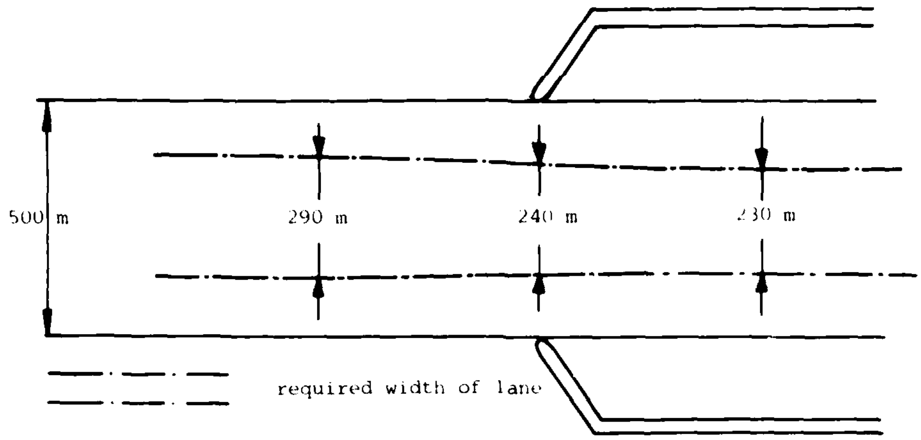


Figure 4. Initial controllability of ship in design
alternative A.

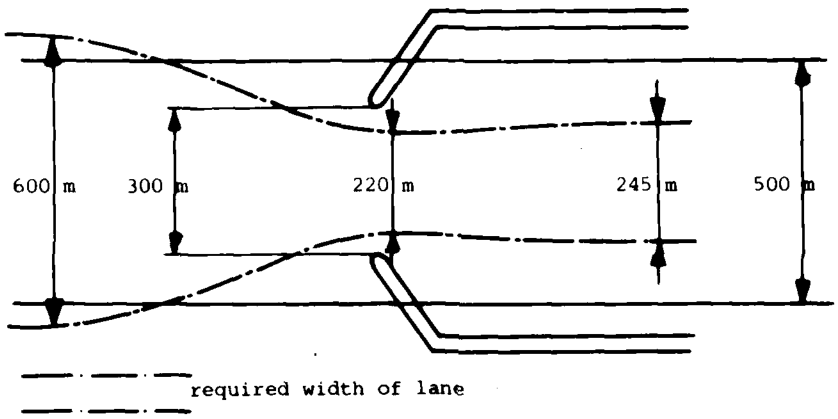


Figure 5. Initial controllability of ship in design alternative B.

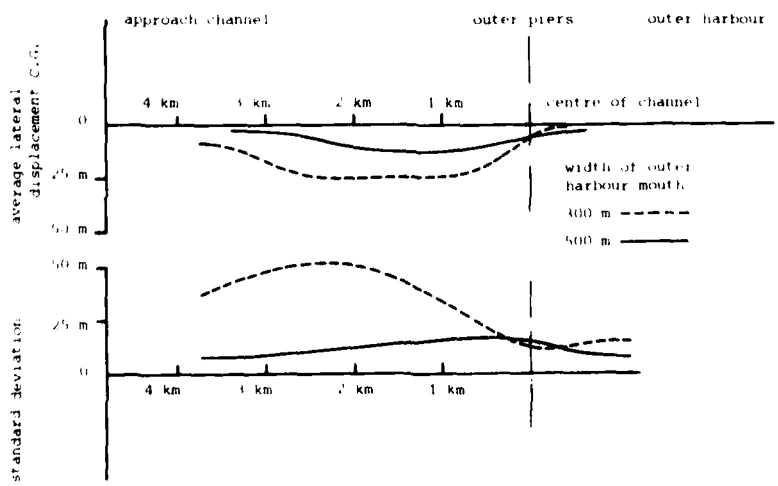


Figure 6. Description of the ship's tracks in design
alternative A or B.

Assessment of Ship's Controllability in the Design Port

In order to proceed to the design of the harbor, some decisions have to be made from a practical point of view. For example:

1. At this stage, changing the starting points of the design to improve the initial controllability of the ship is not recommended.
2. It is assumed that a harbor entrance of 500 m is acceptable from the point of view of wave penetration in the berthing area.
3. Widening of the approach channel from the point of view of initial controllability of the ship has to be rejected.

Based on these arguments, the development of the harbor design now continues with alternative A presented in Figure 4.

It is decided that the time ships wait to enter the port at an appropriate current velocity has to be minimal. When the ships have to enter the port at any moment of the tide, the following values are found:

Required width of lane in the approach channel	~620 m
Required width of lane in the outer entrance	~410 m
Required width of lane in the outer harbor	~525 m
Required width of lane in the inner entrance	~385 m

With respect to the values indicated in Figure 7, the following comments should be made:

1. The widths of lanes determined are preliminary values that hold only for the initial design stage, in which the starting points of the design have not yet been evaluated from economic, hydraulic, and other points of view.
2. The widths of lanes have been determined in a more or less ideal environment in which, for instance, the visibility is clear and information about the current speeds is known to the pilots. When the hydrographical information to the pilots is not accurate, then the waterway has to be much wider to allow the pilot to experience the environmental conditions in which he is sailing.
3. The widths of lanes have been determined using the average track and standard deviation of many maneuvers, as shown in Figure 8.

For the determination of the width of lane, it is assumed that there is a chance (P) of 50 percent that never during the 5500 maneuvers in the waterway will the width of lane be exceeded. When taking into consideration the number of extreme deviations of an outer point of the ship (taking into account ship's length and breadth) from the centerline of the waterway, one finds n = 6930 extremes during the 20-year lifetime of the harbor considered, leading to a chance (1-p) of

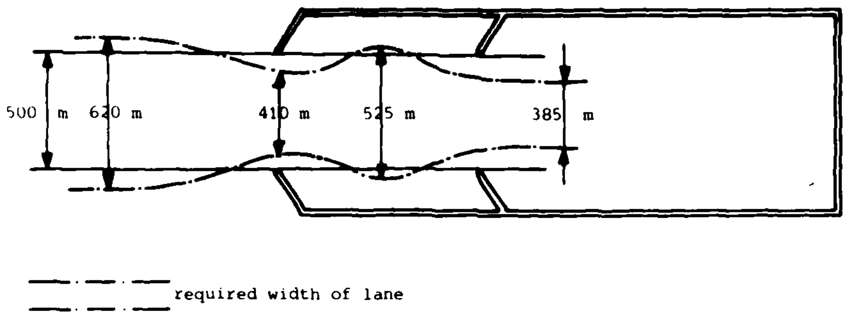


Figure 7. Required width of lane of the ship in the first draft design.

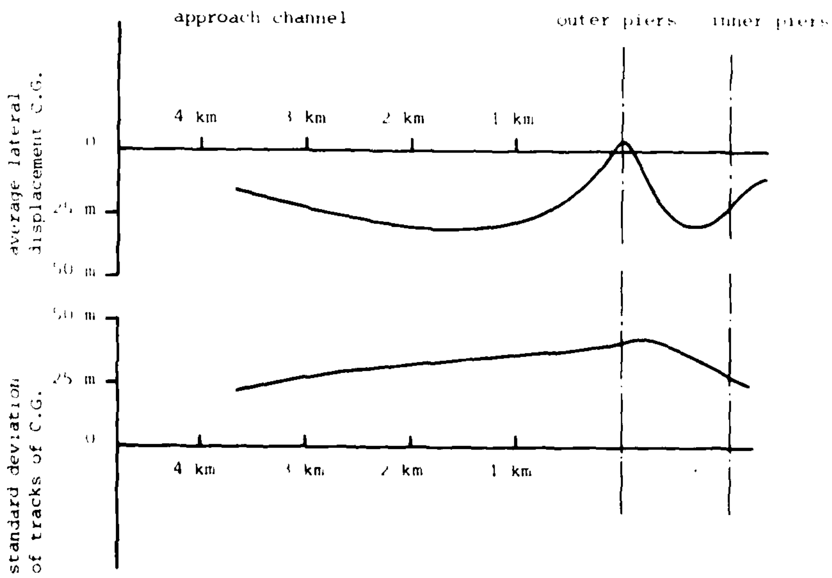


Figure 8. Description of ship's track in the first draft design (see Figure 7).

0.9999 percent that the largest extreme will not exceed the boundaries of the width of lane ($P = (1-p)^n$). Based on the chance p of 0.0001 percent of exceeding the boundaries, these are determined by a factor η, the relation of the maximum and the standard deviation:

$$\eta = \sqrt{-2 \ln 0.0001} = 4.29 \text{ (average)}$$

from which

$$w = 2\,(\eta \cdot \sigma_m + a_m)$$

in which

w = required width of lane
σ_m = standard deviation of plots of extreme points of ship
a_m = average value of plots of extreme points of ship.

4. The values shown in Figure 7 are a consequence of the high level of safety used in the calculations presented above. However, in the initial stage of design, the harbor dimensions seem acceptable relative to the controllability of the ship considered when one neglects these required widths of lane, instead considering the chances of exceeding the given waterway dimensions. One then obtains the following picture:

chance of exceeding dimensions of an extreme in the 500 m approach channel p = 0.015.
chance of exceeding dimensions of an extreme between the 500 m outer piers p = 0.001.
chance of exceeding dimensions of an extreme in the 500 m outer harbor p = 0.004.

From the preliminary values in Figure 7 (determined by the ship's controllability), it can be decided that a first-draft design of the harbor can be:

width of channel	500 m
width of outer entrance	500 m
width of inner entrance	500 m

This draft plan should be further evaluated from hydraulic and economic aspects. It is advised that a detailed draft developed in this way be tested afterwards for its navigational merits. In such a final nautical study, a search can be made for optimum navigability by improving the ship's controllability through a variety of measures specific to the harbor.

In such a detailed nautical study, due attention should also be given to real-life disturbances that exercise an adverse influence on the ship's controllability. Such disturbances include the breakdown of machinery onboard the ship, failures in connecting tug boats, and hindrance of unforeseen obstacles (e.g., maintenance dredges).

Finally, the values presented in this section have been determined from experiments performed at the Netherlands Ship Model Basin ship maneuvering simulator. These figures hold only for the conditions of this specific harbor design and cannot be copied for any other situation without correlation to a range of experiences acquired under other conditions. The figures have been used in this paper only to demonstrate the recommended line of thinking for assessing the ship's controllability in the design of port and harbor entrances.

Effect of Ship's Controllability on the Navigability of a Waterway

It has been noted in the preceding section that many factors will influence the controllability of a ship in a waterway. Decision makers must consider such factors as acceptability of ship size, ship speed, tug assistance, aids to navigation, and others in relation to the available water depth, width of waterway, current patterns, and layout of the port (recommended maneuver).

It will be of no interest to assess the influence of these factors within some subsystem (as for instance, the influence of tug boats on the turning ability of the ship, or the influence of position information on the performance of the pilot). On the contrary, each factor can have tremendous effects on the total system (the piloted ship in the waterway).

The controllability of a ship has been described to this point by the performance of the ship indicated by the deviation of the actual maneuver from some reference maneuver (an intended maneuver or desired maneuver). To assess the navigability of the waterway in a broader sense, one should consider the sensitivity of this performance. In this respect, a very important aspect of the navigability of a waterway is the description, "ease of performing a given maneuver (sailing through the waterway) during operational conditions." The following example illustrates this idea. Compare approach channels, both 300 meters wide, to two different ports, A and B. For port A, the width of lane is required to be 290 meters for ships of different types while port B is designed for a specific type of ship for which a lane 200 meters wide is required. When the chance of an accident in port B is large for a ship that differs slightly from the specified type, then it will be obvious that the navigability of port A is more acceptable than that of port B. The same illustration could be given for the influence of the approach speed on the navigability of a port: the conditions in some ports are such that a variation in the approach speed will not affect the required width of the lane, while in other ports such a variation can lead to undesirable risks.

From these examples it will be understood that the navigability (indicated by "the ease of sailing through the waterway") depends largely on the sensitivity of the ship's controllability to disturbances in daily operational conditions. The general definition of sensitivity leads to the following:

$$s = \frac{\Delta P/P}{\Delta E/E}$$

in which

s = sensitivity--the navigability improves when s becomes smaller
P = performance of the ship determined by its controllability
ΔP = change of performance
E = external factor influencing the ship's controllability
ΔE = change of external factor

When the external factor changes randomly, then the quantity ΔE can be indicated by the standard deviation of the varying factor, while E is the average value of the varying factor. In this case, ΔP is indicated by the standard deviation of the performance index of the ship's controllability.

As no routine exists for developing harbors from a nautical point of view, no methods have yet been developed to analyze the navigability of a waterway according to the paraphrase given above for the sensitivity of the ship's controllability to external disturbances. The most important missing aspect to develop for the analysis of the navigability of a waterway is criteria. In the future, when experience has been gained in using the term "navigability of a waterway," practical criteria can be developed that provide a common-sense understanding of the acceptability of the waterway from a nautical point of view.

In the absence of criteria to answer the question whether a waterway is acceptable when the sensitivity s is known, an elaboration of the meaning of the paraphrase for the sensitivity s will be given here with the help of a few examples.

Example 1. It was seen in the previous section that in zero-current conditions the required width of lane in the approach channel changed from 290 m to 600 m when the width of the port entrance changed from 500 m to 300 m. The sensitivity of the ship's controllability to the 500-meter entrance will be:

$$s_{we} \approx \frac{310/290}{-200/500} = -2.67$$

in which

s_{we} = sensitivity to the width of entrance.

The sensitivity s_{we} of the ship's controllability at a 300-meter-wide harbor entrance is -0.775. The conclusion now reads: the controllability in the approach channel is acceptable with a 500-meter-

wide harbor entrance; however, the sensitivity to the width of the harbor entrance is large. Small changes in the width of the harbor opening will have large effects on controllability. However, in the 300-meter-wide harbor entrance, the ship's controllability is unacceptable, while its sensitivity to the width of the harbor entrance is small. Little gain in controllability can be achieved by widening the opening!

Example 2. It was seen in the previous section that for the design concept A, the required width of lane in the approach channel changed from 290 meters when there was zero current to 620 meters when the ship had to sail in a variety of crosscurrents with a maximum speed of 3 knots. Since the external factor (current velocity during each maneuver) is randomly changing, the sensitivity to current is a little bit more complicated than in the previous example. From the maneuvers performed one determined:

- Required width of lane: 290 m at zero current
- Required width of lane: 480 m at currents with a magnitude of either -1.5, 0, or +1.5 kn during various maneuvers
- Required width of lane: 620 m at currents with a magnitude of either -3, -1.5, 0, +1.5, or +3 kn during various maneuvers.

When it is assumed that the 290-meter width of lane is indicated by the initial controllability of the ship in the design port without disturbances (no current), then the 290-meter width of lane is the initial (zero) width to be considered for the port. An additional 190 meters of width is required when the port is designed for ships to enter during crosscurrents of 1.5 knots maximum (see Figure 9). However, when the port is designed for ships to enter during crosscurrents of 3 knots maximum, then 290 meters has to be added to the required width of lane at the initial controllability. In this way, one finds a sensitivity to current of 1 at zero current ($\Delta P/\Delta E = P/E$ at $E \approx$ current velocity = 0). Note: this amount of sensitivity has no absolute meaning, as it is used only to define a relative measure to the sensitivity at higher values of the crosscurrent. The sensitivity to currents of the ship's controllability in the design port is presented in Figure 9.

From the results obtained earlier, it was concluded that the ship's controllability decreases at increasing current velocity: P (required width of lane), and increases at increasing E (current velocity). However, it can be seen from Figure 9 that the port designed for ships entering as various currents reach the maximum velocity is considered the best navigable port when the channel width corresponds to the required width of lane.

Note: this conclusion would have been reached much easier by considering $\Delta P/\Delta E$. This latter consideration, however, only applies to the present case, and has been ignored because it seemed more interesting to show the general meaning of the definition of sensitivity offered previously.

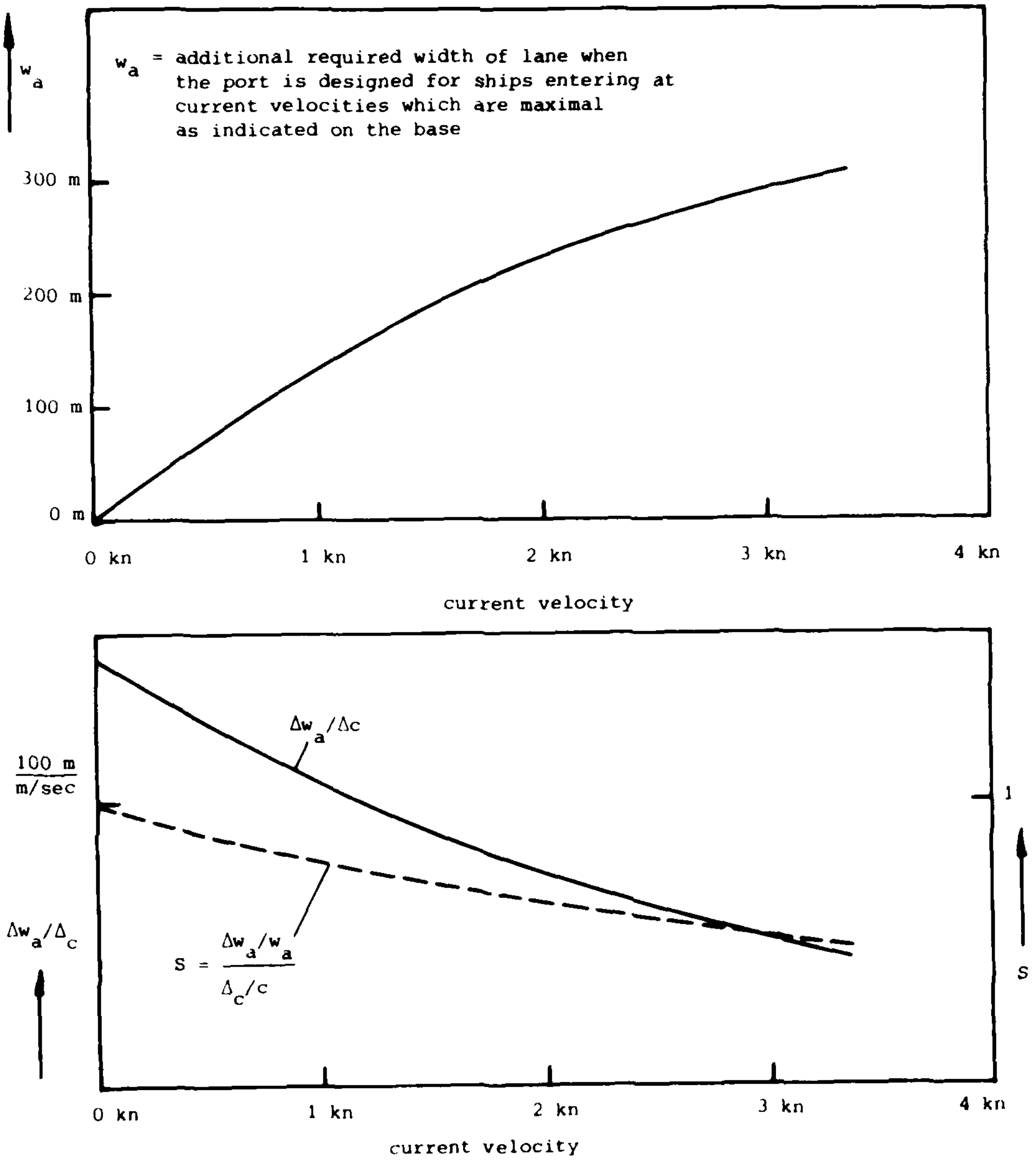


Figure 9: Schematic indication of reduction of the sensitivity to current.

Example 3. In reference 14, the controllability is considered of a 200,000 DWT tanker sailing through a crosscurrent of 0.5 knots average. A peak exists in the crosscurrent of which the amplitude varies between 1, -1.25, -1.5, -1.75 and 2 knots during various maneuvers. When the exact magnitude of this peak is known to the pilot, a required width of lane of 350 meters is observed. However, when the information to the pilot about the magnitude of the peak current is less exact, then the required width of lane increases to:

410 m at an accuracy of 87%
670 m at an accuracy of 75%

One thus finds:

$$s_{ai} = \frac{60/350}{13/100} = 1.32 \text{ for 100\% accuracy}$$

$$s_{ai} = \frac{320/410}{25/87} = 2.72 \text{ for 87\% accuracy}$$

$$s_{ai} = \frac{260/670}{12/75} = 2.42 \text{ for 75\% accuracy}$$

in which:

s_{ai} = sensitivity to accuracy of information.

From the above results it can be concluded that the navigability of a 350-meter-wide waterway with 100 percent accuracy of information about the current is better than the navigability of a 670-meter-wide waterway in which the accuracy of information about the current is 75 percent, while this latter design offers better navigability than a 450-meter-wide waterway in which the accuracy of current information is 87 percent.

In other words, from the results obtained, one could recommend a choice between two alternatives. Alternative 1 is a waterway of restricted dimensions in which correct information about the current is supplied to the mariner. Alternative 2 is a very wide waterway in which the information about the current to the mariner is only a rough estimate.

Safety of Navigation

In the preceding sections, the navigability of a waterway, as influenced by the ship's controllability, is regarded only from the point of view, more or less, of economical operations. Some attention has been given to the optimum use of a port: as many ships should enter the port as easily as possible under most conditions.

However, when considering the controllability of the ship during its passage through the port, the ultimate test is the mitigation of

accidents. Of course, the safety of navigation depends largely on the ship's controllability, but the execution of a risk analysis will cover more than ship controllability alone.

Though the navigability of a waterway is closely related to the safety of navigation in the waterway (and both are influenced by the ship's controllability), different procedures will be employed to specify each.

A true risk analysis necessarily implies a three-step procedure. The first step includes the establishment of the probability of the occurrence of hazards and their associated consequences. (This would presumably include human errors that initiate a chain of events creating a hazard). The second step is an evaluation process to determine the level of risk the system is expected to be subject to, and the third step is the procedure whereby the originally derived level of risk is mitigated by the introduction into the system of certain design changes. actions, operative restrictions, and other factors.

In evaluating any marine transportation system from the point of view of safety, one must utilize a systematic process that infers the level of safety from the aggregate of the individual risks, rather than the individual risks alone. This in itself suggests that a systematic process of risk identification and analysis is necessary to measure the safety of a system.[15]

The problem to date has been the inability to derive a systematic evaluation process that correctly considers all the complex interactive elements that contribute to the occurrence and activation of hazards; namely,

- The ship's inherent hydrodynamic characteristics,
- The "skill" of the mariner in controlling the ship,
- The peripheral aids (either on board or external to the ship) that furnish data or control to the mariner, and
- The effects of a particular environment (port geophysics, wind, current, channel width and depth, other vessels, etc.) on the vessel and the operator.

To approach this complicated problem, it is of primary importance to acquire reliable data from actual practice. To this end, good correlation must be available between what in fact occurred and the reports of persons involved. It is no surprise that accurate measurements are limited by instrumentation and the conditions under which marine casualties occur. Moreover, human perception is highly subjective. This has led to the generally accepted theory that there are more accidents than are actually reported. This problem can only be solved when the reports are scrutinized more closely and the hypothesis that accidents are intentionally concealed is disregarded.

Another discrepancy in the reporting system derives from the physiological and psychological characteristics of men involved at the time of an accident. Since among other things, a clear definition of mental load is lacking, it is difficult to establish a criterion of allowable stress.

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PROBLEMS AND OPPORTUNITIES IN THE DESIGN OF ENTRANCES TO PORTS --ETC(U)
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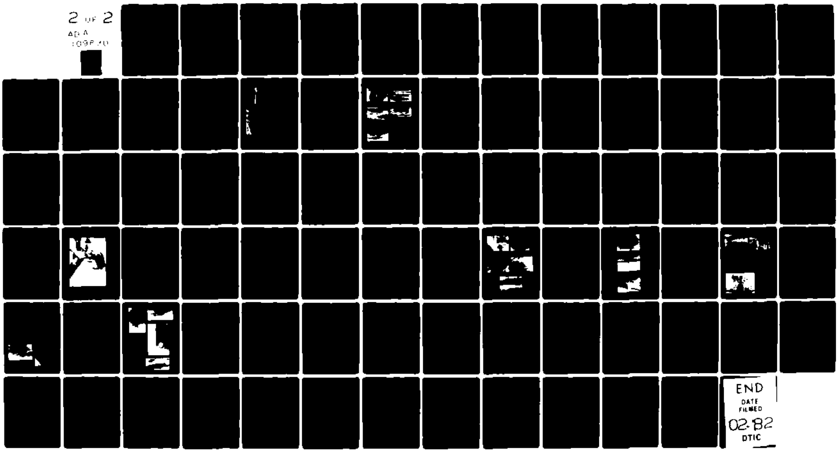

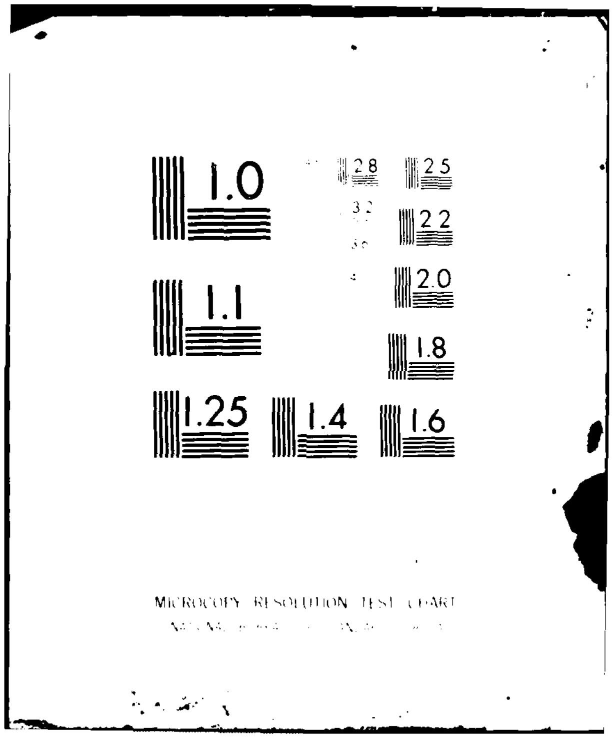
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MICROCOPY RESOLUTION TEST CHART

Concluding Remarks

Ship controllability exerts a large influence on the navigability and safety of a waterway. In assessing a ship's controllability, no absolute measures can be defined because many factors related to the properties of the ship and of the waterway are important.

To reach an improved understanding of a ship's controllability as it determines the nautical requirements to be imposed on the dimensions of a waterway, more basic research must be conducted. The results of such investigations would provide port designers the information to set up a first-draft design of the port.

When such a draft has been evaluated from economic, hydraulic, and other points of view, adequate means are available to ascertain the final merits of the port from a navigational point of view.

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DISCUSSION

WEBSTER: In your Figure 7, you show a required mean width of lane. As a result of the studies you conduct, is that the width you recommend to be dredged? If you were trying to *minimize* port costs, would you dredge the lane that way, or would you try something else?

HOOFT: For these figures, suppose you had 500 meters available, and available information indicated that you required 620 meters. Then I would say, look at the higher requirements you would apply to this figure; for example, "I want 50 percent safety over 2000 maneuvers of ships," etc., and when you look at the other possibilities available for mitigating the chance of accidents at 620 meters, then I would say which is the just concept or first draft? Then look to see if 500 meters is acceptable from a hydraulic point of view. Do you have acceptable wave penetration in this inner harbor? Is the wave penetration of the docked ships excessive? Then you must take other measurements. For designing a harbor, you want some indicative requirements for deciding dimensions: information about controllability, for example. Then you must look from all the other points of view to see if the evolving design is acceptable for the controllability assumed and for safety.

KRAY: The maneuverability of the ships you discussed, is that for an automatically controlled ship excluding all human elements. For example, is the delay in the transmission of orders to the engine room considered, or the response of the ships to the actions of the handler? It appears that you have considered rudders of the conventional type in these studies. Have you given attention to the

flat-belt type that is far more effective in keeping the ship on course and in preserving its maneuverability?

HOOFT: What you are indicating is that the total system is composed of so many aspects! The human element you mention, for example. Your question is, was the skill of the shiphandler considered in the performance of the maneuver? The overall system can be improved by increasing the skills of the people involved. The ship's maneuverability can be influenced by the rudder configuration, the stern configuration, the dimensions of the ships. My plea in making this presentation is that when you are not satisfied with the ship-harbor interaction, it will not do--as was common 10 years ago--to blame the dimensions or characteristics of the ships. In the past three or four years, it has become common to cite human error. In another four years, the blame for accidents may fall on the navigational aids! Elements of the system cannot be singled out, as you and Bill Webster indicate by your questions. The decision about channel width and any other in the design is a compromise effected among all the concerns the designer is trying to meet, most importantly, the navigability of the waterway.

HARLOW: On one hand, we're talking about balancing the capital costs and the operating and maintenance costs of a whole series of steps one might take dealing with the ships, the harbor, the channels, and so forth. On the other hand, we're talking about accidents. We should be looking at the consequences of certain kinds of accidents that will occur if proper steps are not taken, and the costs. We have never tried to do this in a systematic way that I know of, but if we did, we would have to look at other items, and make a full systems analysis.

SEARLE: I want to endorse that. There is too great a tendency when an accident happens--and all I see is accidents--to cite human error as the cause. I've seen many accidents that were inevitable. The unusual aspect of many accidents is that more have not occurred in the same place. There have been two major accidents in Tampa Bay since the first of the year. Both were inevitable. Seconding what Gene Harlow said, systems analysis ought to pinpoint those hazardous locations. Your presentation highlights the integration of ship maneuverability or controllability with harbor design: the system also needs hazards analysis, failure mode and effects analysis.

CRANE: I'm fully in accord with full systems analysis. We must accept certain constraints and givens: while it would be helpful if all shiphandlers were fully trained, for example, their range of ability must be accepted. Then we are in a position to work with channel dimensions, aids to navigation, vessel traffic systems, and other parameters to improve safety.

HARBOR ENTRANCE DESIGN: A PILOT'S VIEW

Captain Thomas G. Knierim

I am a New York ship's pilot, and my topic is pilots' concerns. After any and all the engineering and theoretical studies for harbor design have been developed and a vessel arrives at the entrance to this harbor, I am the one who must make the round peg fit into a square hole, or explain why it doesn't fit.

It seems that in the past as the shipping of the day grew in size and draft, and problems arose, channels were enlarged just enough to permit those vessels to move under favorable conditions. A case in point seems to be the busy Houston Ship Channel which is dug to a width of 400 feet and continually accommodates tankers in the 100,000 DWT class. A pilot told me the U. S. Army Corps of Engineers will not widen the channel because there are not enough accidents to warrant it. It would seem that to lobby for a safer channel you must first become more slovenly in your piloting techniques. We wait for a calamity before doing anything constructive. To strengthen this point--though I know only some of the newspaper accounts of the tragic Tampa Bay accident--it was reported that a member of the state bridge commission (after several prior accidents) likened protection around the bridge tower dock structures to placing a metal shield over every home in the United States for protection from falling aircraft. Nonetheless, such protection has been placed around several New York bridges with satisfactory results.

It must be said that we, the practical navigators, are quite skeptical about relations with government agencies. In cases such as harbor traffic control, rather arbitrary decisions have been made.

To understand the pilots' views on harbor and port entrance design, we must really take into account the needs of both the foreign mariner arriving at a strange port with a large, fully laden vessel and attempting to find his pilot, and the pilot coming aboard a vessel foreign to him. The pilot is required to locate the ship's position and to provide safe, economical pilotage aboard this unfamiliar ship during the day and night and during all extremes of weather. In both instances, our needs can be expressed as the questions, Where am I? (ship's position), Where do I want to go? (local knowledge), and, How do I get there? (ship-handling ability). The last two represent the necessary ingredients of pilots.

The question, Where am I? in a major seaport demands an outstanding aid to navigation equipped with a major light, sound signal, radio direction finder, and racon, etc., to distinguish it from all other aids or vessels. It is then an incoming beacon for the approaching mariner and a point of departure for a pilot. In a small port, such as Bridgeport, Connecticut, when approaching from the west, a light ahead (Stratfort Point Light), and when close to the mid-channel buoy, a light abeam (Penfield Reef Light), is ideal.

Where am I going? As a pilot, my primary desire is a wide channel. It might be said that as the roadstead widens and becomes good water, as in a fjord or some sounds, the need for navigation aids lessens. Should we dig a channel this wide, our need to mark it diminishes or becomes nonexistent. Conversely, as the channel narrows, the need to mark it well increases. A 2000-foot-wide channel, such as Ambrose leading into New York, is regularly run in poor visibility using radar, without undue apprehension. As the channel continues to diminish in width to, say, 500-800 feet, the potential for near-misses and collisions increases at an accelerating rate.

The entrance to a well-marked channel should, whenever possible, be marked with a mid-channel buoy, one to two miles off shore from the buoyed channel to give a good approach.

The most valuable aid to navigation today, and the most basic aid, is a well-lighted sound buoy. Properly placed, in position, and in sufficient number, they indicate within a number of feet where the channel limitations are. Whenever possible, buoys marking channels should be gated. There seem to have been few changes to buoys in years, and their total number in an age of increasing ship size does not seem to have increased. Interestingly, when we ask for a buoy to mark a particular point, we often hear, "Glad to move one, where should we move it from?" You get the feeling that not a single buoy has been built since my grandpa worked for the lighthouse department.

Since buoys can move, some permanent structures should be considered, especially near turns in areas experiencing difficulties from ice or storms, or where they are often dragged by vessels. Lights should also be maintained under bridges to mark channels.

Another basic useful aid to a mariner is a set of range lights. They are particularly valuable in the first leg of a channel, where there is a greater chance of tidal set. Entering or exiting a port such as Port Jefferson with a 300-foot channel at night in a winter gale, the range is used almost to the exclusion of the buoys.

Electronic gadgets have emerged during the 20th century, notable for their advancement of navigation and also for their degree of unreliability during times of stress. During a symposium several years ago, an officer of Gulf Oil discussing collision avoidance systems (CAS), said his company experienced a breakdown rate of about 5 percent with the radar and about the same with the CAS, creating a multiple of unreliability for the CAS.

Our most-used aid, the radar, the pilot uses aboard an unfamiliar vessel. The radar may be in almost any state of repair or tuning. It must be considered that we shrink a three-mile radius into about a foot on the three-mile range. Therefore, determination of position in, say,

a 2000-foot channel, which is about the width of my thumb, is truly by rule of thumb. Loran and Deca will give a position within 50 feet or so in some areas. However, aboard merchant ships, personnel is insufficient to keep an up-to-date running check as a cross-reference for the pilot. We have Dopplers and rate-of-turn indicators that can be useful, but in a channel situation, these are difficult to incorporate fully into navigational procedures.

This brings us to a quite interesting aid, used today in the man-made port of Antifer, near Le Harve, France, which quite possibly could have prevented the tragedy in Tampa Bay--the transponder. During experiments with this device (for example, in channel situations at the Computer-Aided Operations Research Facility), a very informative readout was obtained regarding longitudinal position from the channel's center-line, and the rate at which the vessel was transversing either left or right. It also gave a readout for the distance to the next turn. A system that uses a shore station, when receiving signals from two transmitters located fore and aft on the centerline of the vessel, instead of just one transmitter at the center of the ship, will also give the vessel's rate of turn in a bend.

Pilots are as interested as anyone in navigational advances for harbor and entrance design. However, we must stress that electronic aids be provided in addition to a complete set of basic navigational aids, and never to the exclusion of those aids.

I have purposely disregarded the depth of the channel, which I personally like at least 1.2 times the ship's draft for ease of handling. This is because pilots must often exercise their abilities in less than ideal conditions. If a vessel will float, we will move it safely at a slow rate. I have also omitted vessel traffic control because so much has been said about it lately. Vessel traffic control should aid the mariner, not add to his burden.

DISCUSSION

MAGOON: I would just like to make a comment. For many of the channels, at least the federal channels that are constructed and maintained by the Corps of Engineers, some of the problems you mention come up in public hearings when the project is under review. If the problems need review, a resolution is introduced in Congress and a study is authorized of the particular channel. On the study's completion, the recommended changes would be made.

WEBSTER: One of the problems, I would imagine, with port design is that you have to design the port so that many different types and sizes of ships can come through it. I was wondering whether you have any insight into the most demanding types of ships that you have to drive through the New York harbor. Are the biggest ones the hardest to handle? Do you have any feel for what it would be that is the most critical in handling?

KNIERIM: Some of the larger ships, passenger ships, are quite easy. Loaded tankers are difficult ships to handle because of their size and weight. I think something that has been found, though I haven't handled a VLCC* as such, is that the control of these ships, with the amount of mass that they have, the forces created by their movement through the water, and various interactions place demands on the pilot. The SL-7s, because of their size and handling abilities, are very difficult ships. The most difficult part of the SL-7 pilotage in the New York harbor is done by the docking masters and not by the sea pilots.

One difficulty in piloting an SL-7 is that the wheelhouse is all the way forward. The pilot therefore has lost a lot of his perspective, being right on the bow. He doesn't get a feeling of the ship's mass, and he can't see just what the ship is doing, so the pilot usually doesn't stand there, but prefers to stand more or less in the midship house where some of the stacks are.

He gives his commands by radio to the pilot who is in the wheelhouse, and it is then passed on to the quartermaster for steering. Interestingly, if he tells them that he wants 10 degrees right rudder, they put the rudder over 10 degrees right, but the tugboat on the stern starts working slow ahead on the starboard quarter. If he increases the rudder to 20 degrees right rudder, the tugboat on the quarter increases speed to half ahead on the starboard quarter and if he says hard right, the tugboat hooks it up. Those ships don't handle well, and pilots derived the system of turning them with their rudder commands, automatically giving a signal to the tugboats and assistants to help them turn.

Container vessels, because of their size and the sail area in a good breeze or wind, are most difficult to handle, and require special caution.

LE BACK: As a pilot, would you support or advocate moving the pilot boarding area farther out to sea, for those large vessels particularly? Licensing would have to be changed and extended, and of course, the question of additional pilot fees for extending this pilot ground further to sea would have to be resolved. Would you support something like that if it were in the interest of the safety of the port?

KNIERIM: The captain of a foreign, heavily laden ship coming to the port for the first time is apprehensive. There should be a good light, a good beacon, bringing him in so he knows where he is, but there should be no reason for him to be overly apprehensive. The assumption of pilotage should take place long before the ship is in any real danger. There should be time for the pilot to come aboard the ship and to receive the command from the captain without any difficulties occurring before or during the passage of the command to the pilot. Therefore, I should say that if the pilotage area is not sufficiently offshore for that particular type of ship, moving it farther out should definitely be considered.

*Very large crude carrier.

NATURE AND ENVIRONMENT

SEDIMENTATION IN HARBORS

J. W. Johnson

Introduction

The discussion to follow is concerned primarily with the type of sedimentation that normally might be expected to create design, operation, and maintenance problems in harbors, ports, and offshore terminals. The most comprehensive and yet concise coverage of this important sediment problem is that presented by Caldwell.[1] The types of harbors discussed in his treatment are listed as follows, with some actual harbors given as examples:

River-Channel Harbors

Baton Rouge, Louisiana
St. Louis, Missouri
Pittsburgh, Pennsylvania
Sacramento, California (old harbor)

In such harbors, the fresh river waters keep the clays moving; consequently, the principal sedimentation problem becomes one of sand. Dredging, training walls, and diversion of the river, are the usual corrective measures in such harbors.

Off-river harbors

These harbors have little difficulty with sand and gravel, but do often have problems with silts and clays. The solution to shoaling is dredging, training walls and dikes, and use of locks or floodgates.

Fall-line harbors

Troy, New York
Washington, D.C.
Richmond, Virginia

Sedimentation problems generally result from sand and gravel deposits. Solutions usually consist of dredging, training walls, or the creation of an off-channel harbor.

Off-channel harbors in tidal estuaries

Washington, D.C., Channel Harbor
Houston, Texas
Sacramento, California (new harbor)

Shoaling is usually due to suspended silt and clay. Improvement is the same as for off-channel river harbors--namely, dredging, training dikes, and use of locks.

Shoreline harbors

Santa Barbara, California
Santa Monica, California
Camp Pendleton, California

The problem at such localities is the deposition of sand moved into the harbor by littoral currents (discussed in the succeeding section). Maintenance of such harbors usually involves a sand-bypassing operation, as also discussed in another section.

Sand Transport by Littoral Currents

General Considerations

The result of waves breaking at an angle to a shoreline is generation of an alongshore or littoral current. It is this current, combined with the agitating action of the breaking waves, that is the primary factor causing the movement of sand along a coastline. This movement takes place in two manners--in suspension, and by rolling in a zigzag motion along the beach face. For a beach with an equilibrium profile formed by waves of relatively large steepness, which is characteristic of storm conditions, the sediment movement is mainly in suspension.[2] In the case of an equilibrium beach profile formed by waves of low steepness, which is typical of calm summer conditions, the transport appears to be the result of rolling or skipping along the beach face. It is believed that as much as 80 percent of the material moved by wave action is moved in the area shoreward of the breaking point.

Rate of Drift

As yet, no general relationship between wave and sediment characteristics is available for estimating the rate of littoral transport that occurs along a given shoreline. A few early laboratory experiments have assisted in defining the important variables.[3/4] Since these early studies, a considerable number of field and laboratory investigations have been conducted. The fundamental mechanics of littoral transport have been summarized recently by Komar and Inman[5] and Komar.[6] Numerous measurements of rates of transport along natural shorelines have been estimated from the amount of material trapped by man-made shoreline structures. A summary of such measured rates along U.S. coasts, as recently compiled by the Coastal Engineering Research Center, is presented in Table 1. The reader is referred to the Shore Protection Manual for the general procedure in estimating rates of drift for a locality where the wave characteristics are known.

Predominant Direction of Littoral Transport

The direction of littoral transport at a particular time is dictated by the direction of the alongshore component of the wave velocity at the breaking point (Figure 1). On many coastlines, important reversals in the direction of littoral drift occur because of the seasonal variation of the direction of wave attack. Usually, however, the intensity of wave attack predominates in one direction, with the resulting in a net or predominant direction of drift. For the locations for which rates of transport are given in Table 1, the predominant direction also is given. Undoubtedly, the drift occurs in one direction along the various coastlines at certain times of the year, and in the opposite direction during the remainder of the year; however, a net drift occurs in the direction and at the rate indicated. For example, along the south Atlantic coast of the United States the littoral drift is northward during the summer season when light winds from the south and southeast prevail, but during the fall and winter, strong northeasterly storms, accompanied by relatively high seas, drive the sand southward. These winter storms are more severe than the summer storms, with the result that the predominant drift is southward along the south Atlantic coast.

The determination of the predominant direction of littoral transport has long been a study of interest to the geologist. In many instances, it is necessary to know both the direction of littoral transport at any one time and the predominant direction of littoral transport over a normal climatic cycle. The predominant direction is the more difficult to determine, and may involve locating the position of natural and unnatural littoral barriers and those areas called nodal zones in which the net littoral transport changes direction. In these zones, the net littoral drift is zero, or in other words, the downdrift components of littoral drift are equal to the updrift components. An excellent example in this respect is the coast of New Jersey where

TABLE 1. LONGSHORE TRANSPORT RATES FROM U.S. COASTS*

LOCATION	PREDOMINANT DIRECTION OF TRANSPORT	LONGSHORE[a] TRANSPORT (cu.yd./yr.)	DATE OF RECORD
	Atlantic Coast		
Suffolk County, N.Y.	W	200,000	1946-55
Sandy Hook, N.J.	N	493,000	1885-1933
Sandy Hook, N.J.	N	436,000	1933-51
Asbury Park, N.J.	N	200,000	1922-25
Shark River, N.J.	N	300,000	1947-53
Manasquan, N.J.	N	360,000	1930-31
Barneget Inlet, N.J.	S	250,000	1939-41
Absecon Inlet, N.J.[b]	S	400,000	1935-46
Ocean City, N.J.[b]	S	400,000	1935-46
Cold Spring Inlet, N.J.	S	200,000	---------
Ocean City, Md.	S	150,000	1934-36
Atlantic Beach, N.C.	E	29,500	1850-1908
Hillsboro Inlet, Fla.	S	75,000	1850-1908
Palm Beach, Fla.	S	150,000 to 225,000	1925-30
	Gulf of Mexico		
Pinellas County, Fla.	S	50,000	1922-50
Perdido Pass, Ala.	W	200,000	1934-53
	Pacific Coast		
Santa Barbara, Calif.	E	280,000	1932-51
Oxnard Plain Shore, Calif.	S	1,000,000	1938-48
Port Hueneme, Calif.	S	500,000	---------
Santa Monica, Calif.	S	270,000	1936-40
El Segundo, Calif.	S	162,000	1936-40
Redondo Beach, Calif.	S	30,000	---------
Anaheim Bay, Calif.	E	150,000	1937-48
Camp Pendleton, Calif.	S	100,000	1950-52
	Great Lakes		
Milwaukee County, Wis.	S	8,000	1894-1912
Racine County, Wis.	S	40,000	1912-49
Kenosha, Wis.	S	15,000	1872-1909
Ill. State Line to Waukegan	S	90,000	---------
Waukegan to Evanston, Ill.	S	57,000	---------
South of Evanston, Ill.	S	40,000	---------
	Hawaii		
Waikiki Beach[b]	-	10,000	---------

[a]Transport rates are estimated net transport rates, Q_n. In some cases, these approximate the gross transport rates, Q_g.

[b]Method of measurement is by accretion except for Absecon Inlet, and Ocean City, New Jersey, and Anaheim Bay, California, by erosion and Waikiki Beach, Hawaii, by suspended load samples.

*SOURCE: U.S. Army Corps of Engineers, Shore Protection Manual, Vol. I (Washington, D.C.: Government Printing Office, 1973), p. 9 (Table 4-6).

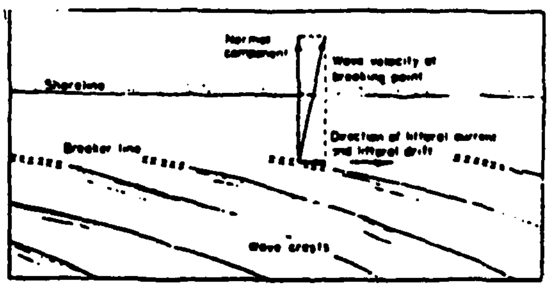

Figure 1. Components of wave velocity when waves break at angle to shoreline.

extensive study of sand movement by the Corps of Engineers and others has established that a nodal point occurs at Manasquan, New Jersey, with the predominant drift being northward north of this point and southward south of this point.

Although the methods used in determining the direction of littoral transport may differ from place to place, determination of the instantaneous and predominant directions of littoral transport and the location of littoral barriers and nodal zones ordinarily is accomplished by consideration of such factors as (a) shore patterns in the vicinity of headlands, (b) the configuration of the banks and beds of inlets and streams, (c) accretion of erosion effects of man-made structures, (d) statistical analysis of wave energy, (e) characteristics of beach and bed materials, and (f) current measurements.

Another item of importance with respect to currents is the confusion that often occurs between the strength of the littoral currents and the strength of the large-scale ocean currents. These latter currents, as measured by the drift of bottles and floating debris, usually are relatively weak as a sand transporting agent compared to the wave-induced littoral current. At localities where these two currents are opposed, the wave-induced littoral current usually is the stronger of the two, and therefore determines the predominant direction of littoral drift.

Sediment Transportation, Deposition, and Erosion at Man-Made Littoral Barriers

There are three basic types of man-made coastal structures that function as littoral barriers: a dredged channel, a jetty or groin, and an offshore or detached breakwater.[7] The littoral processes in the vicinity of such works are summarized briefly here.

Dredged channels. Harbors are often connected with deep water offshore by means of a dredged channel through the littoral zone (Figure 2). Such a channel creates greater than normal depths with the result that littoral material accumulates therein. Sediment of small enough size to be moved in the deeper depths seaward from the end of the dredged channel would not, of course, be affected. Measurements indicate that most of the longshore transport of material occurs in the vicinity of the breakers where the available wave energy is converted suddenly from an oscillatory motion into the form of turbulence. For that portion of the wave that moves over a dredged channel, however, breaking does not occur, because of the increased depth, and the wave energy passes the normal point of breaking to be spread by refraction and dissipated further inshore. The degree of turbulence, therefore, is insufficient to transport material across the channel and the material accumulates approximately as indicated in Figure 2. To maintain the channel in a navigable condition, this accumulation of littoral material must be dredged periodically. If this material is removed and redeposited on the downcoast side of the channel, normal littoral transport will occur in that region, and the shoreline will

remain in an equilibrium position. If, however, the channel deposits are placed elsewhere, then the supply of material to the downcoast beach is reduced and erosion and retreat of the shoreline probably will result (Figure 2). In a harbor such as shown in Figure 2, the action of the waves is to restore the natural littoral transport of material and thus reduce the area of the entrance to a size compatible with the tidal prism. The equilibrium size of entrance to be expected might be estimated by the relationships between entrance area and tidal prism as given by O'Brien.[8]

Harbors created by shore-connected breakwaters. The effect of a structure that extends seaward from the shore and across the littoral zone is to act as a dam and trap the littoral drift. The impounding capacity is dependent on the height of the structure, the bottom slope, and the equilibrium alinement of the shore in that region. The equilibrium alinement is one which is normal to the resultant littoral forces. Thus, in Figure 3, if the original shoreline was stable with respect to the material balance and a breakwater is constructed as shown, accretion will first occur in the form of a fillet on the upcoast side with an alinement tending toward equilibrium. This will create a deficiency in material supplied to the downcoast shoreline, in which erosion probably will occur with the shoreline also tending toward equilibrium. As the upcoast fillet approaches equilibrium, littoral material will move along the outer face of the breakwater and be deposited in the relatively calm water in the lee of the structure. Thus, the turbulent character of the wave action upcoast from the breakwater tip is sufficient to transport littoral material at capacity. As the waves reach the tip, however, and are refracted and diffracted into the lee of the structure, the turbulence is insufficient to transport the material and deposition occurs. The deposit continues to grow toward the downcoast shoreline, and when it reaches the shoreline the material balance will be re-established on each side of the barrier. The alinement of the harbor deposit depends primarily on the predominant wave direction. A typical example of such a harbor deposit is that at Santa Barbara, California.

A variation of a harbor formed by a shore-connected breakwater is the case where two breakwaters must be provided to ensure protection from storm waves that may approach the entrance from various directions. Pronounced reversals in the direction of littoral drift usually occur in such instances.

Detached breakwater. This type of structure intercepts the waves and creates a protected area of relatively calm water. The original theory of such a breakwater location was that the littoral material would move along the coast uninterrupted by the presence of the structure, and consequently, no maintenance problems from sediment deposition would be created. This assumption, however, is in error. The result of the refraction and diffraction of the waves behind the structure is to reduce the energy available for littoral transport in the lee of the structure as compared with the energy available on both the upcoast and downcoast shorelines (Figure 4). The result of this

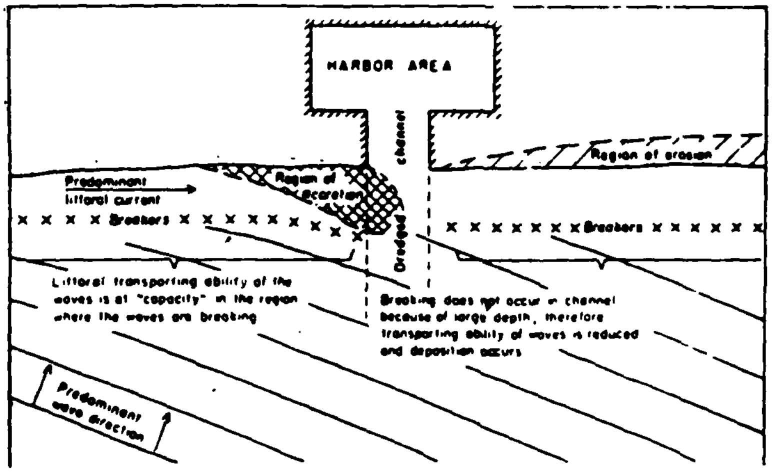

Figure 2. Schematic representation of transportation, deposition, and scour of littoral sediments at channel dredged through littoral zone.

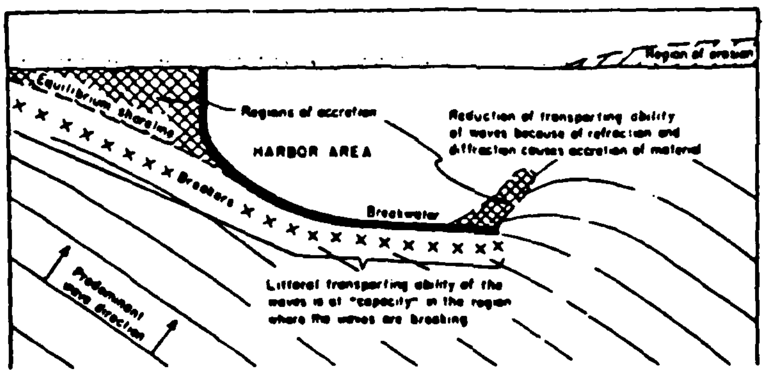

Figure 3. Schematic representation of transportation, deposition, and scour of littoral sediments at shore-connected breakwater.

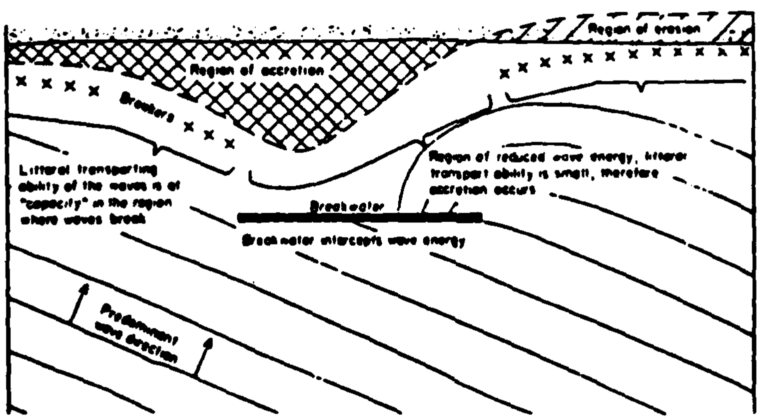

Figure 4. Schematic representation of transportation, deposition, and scour of littoral sediments at detached breakwater.

reduction in available energy is that littoral material accumulates in the protected area. If this accumulation of material is not removed periodically by dredging, the accretion eventually may extend completely out to the breakwater in the form of tombolo.

On the upcoast side of a detached breakwater, the accretion advances beyond the region directly affected by the structure itself, and corresponding erosion occurs on the downcoast side (Figure 4). A typical example of a harbor of this type is that at Santa Monica, California.

Sand Bypassing

A coastal inlet may be considered, for the purpose of this section, as any relatively narrow waterway connecting the sea or large lake with interior waters. Such inlets, either in their natural state or improved to meet navigation requirements, tend to interrupt the normal littoral transport along the shore. In the case of natural inlets that have a well-defined bar formation on the seaward side of the inlet by way of the outer bar, but intermittent, rather than regular, supply reaching the downdrift shore, the result is that the shore downdrift from the inlet is normally unstable for a considerable distance. If the strength of tidal flow through the inlet into the interior body of water is appreciable, part of the available littoral drift is permanently stored in the interior body of water in the form of an inner bar, reducing the supply available to nourish downdrift shores. In the case of migrating inlets, the outer bar normally migrates with the inlet, but the inner bar does not; the inner bar increases in length as the inlet migrates, thus increasing the volume of material inside the inlet.

When the natural depth of an inlet is increased by dredging, either through the outer or inner bars or the channel, additional storage area is created to trap the available littoral drift, thereby reducing the quantity that would naturally pass the inlet. If the material dredged (either for opening or for channel maintenance) is deposited beyond the limits of the littoral zone, as in the case of disposal in deep water at sea, the supply to the downdrift shore may be virtually eliminated, with consequent erosion at a rate equivalent to the reduction in supply.

The normal method of inlet improvement has been to provide jetties flanking the inlet channel. Jetties may have any or all of the following functions: to block the entry of littoral drift into the channel; to serve as training walls to increase the velocity of tidal currents and thereby flush sediments from the channel; to serve as breakwaters to reduce wave action in the channel; and to prevent further inlet migration. In cases where there is no predominant direction of littoral transports, jetties also serve to stabilize the adjoining coastal shores. In the more common cases where littoral drift in one direction predominates, jetties cause accretion of the updrift shore and erosion of the downdrift shore.

Stability of the shore downdrift from inlets, with or without jetties, may be improved by artificial nourishment to make up the

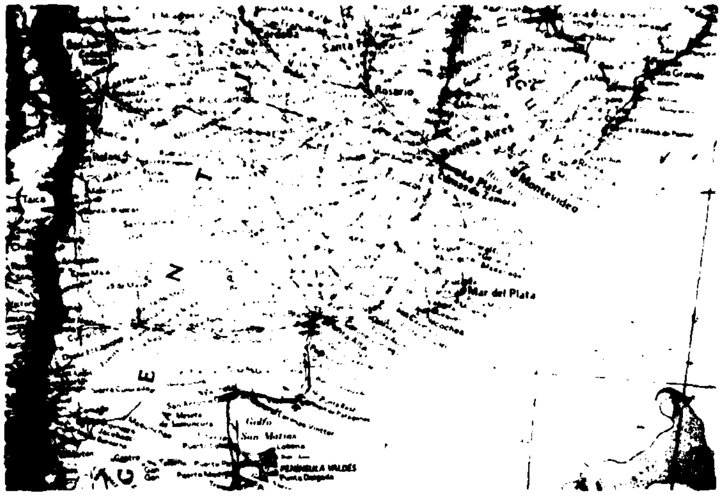

Figure 5. Area of littoral drift affected by waves from several directions, Bahia Blanca, Argentina.

Figure 6. Sedimentation patterns in Bahia Blanca.

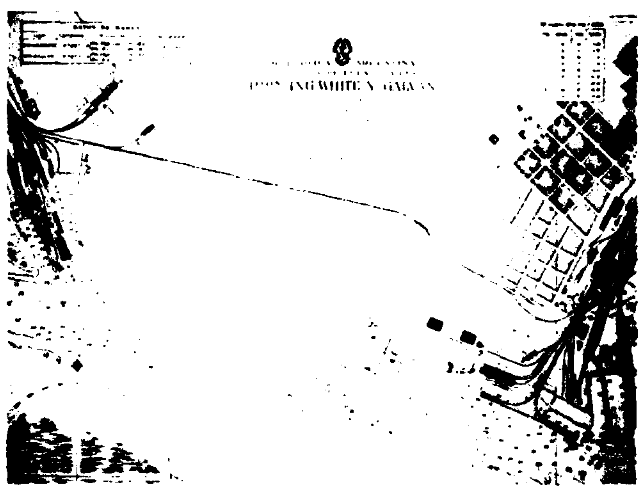

Figure 7. Harbors in tidal estuary.

deficiency in supply. When such nourishment is accomplished by using the available littoral supply from updrift sources, the process is called sand bypassing. A number of mechanical methods of sand bypassing have been employed; however, this is still a relatively recent engineering development, and additional methods will no doubt be developed as experience is gained.

Several techniques have been (and are now) employed for mechanically bypassing littoral materials at inlets. Sometimes a combination of techniques has proved to be the most practicable and economical. The basic methods which have been used are:

- Land-based dredging plants,
- Floating dredges,
- Mobile land-based vehicles.

For details on these methods, the reader is referred to the Coastal Engineering Research Center's Shore Protection Manual, which describes the use of these methods at specific localities.

Examples

The action of these forces, and their interaction with harbor and port design, can be seen in a particularly challenging area on the coast of Argentina (Figure 5). The large estuary of Bahia Blanca has no streams of any importance feeding into it: the sources of sediments are the Rio Colorado, the Rio Negro, or both. Notice that whatever the direction from which waves come--south, southeast, west, even to some extent, northeast--littoral drift will occur along the coast, moving material into the entrance of Bahia Blanca. The sink where all this material arrives is shown in Figure 6. The material is principally sand from the large rivers, and from minor beach erosion and small streams up coast. There are no structures at the entrance: the only developments are the buoys.

Some harbors within the tidal estuary are dredged back into the mud flats pictured in Figure 7. The problem in this area of tidal flats is almost entirely one of cohesive sediments, or wash flow. With each range in tide (about 15 to 20 feet), the sediments are washed back and forth. About 10 feet of sediments are deposited each year, and must be removed by dredging. Dredging is accomplished by the dredge shown in Figure 8, a museum piece, and barged to the middle of the stream where they are dumped, most likely to return with the next tidal range. The pier in the harbor pictured in Figure 9 projects into the tidal stream. Notice the steeply banked channels. The high particle velocity in these channels creates turbulence in flow through the pier: the particles collide and settle faster than they would otherwise.

The grain elevators shown in Figure 10 store the principal export, grain from the pampas. The principal import is oil for the surrounding area.

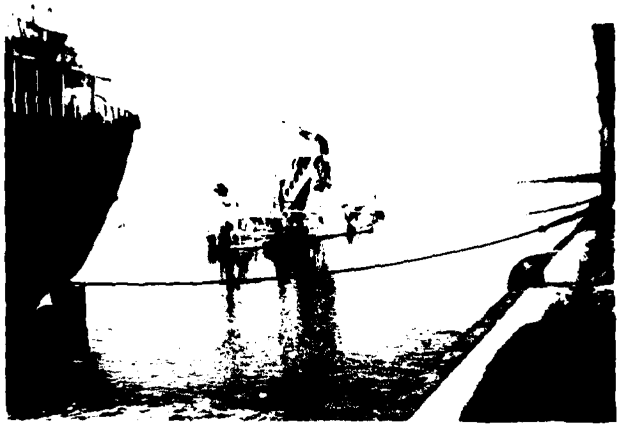

Figure 8. Dredge used to remove sediments in channels and harbors.

Figure 9. Pier projecting into tidal stream.

Figure 10. Pier facilities for grain exports.

Figure 11. Pier built parallel to tidal stream.

Figure 12. Mud flats.

Downstream from this pier is another (Figure 11) that offers a useful contrast. Notice that the pier is parallel to the flow of the tidal stream, and almost sediment-free. The depth is always 23 to 30 feet along the pier face.

A small-craft harbor for tugs and boats is also illustrated in Figure 11, to the left. Some sedimentation can be seen at the entrance, a dead-water area. The principal tidal currents keep the main channels open, but the accumulations of fine materials eventually become cohesive sediments at the entrance to the tug harbor, which is somewhat restricted. The flow of sediments from the mud flats (Figure 12), owing to the high tide range, cuts extremely steep, sloped channels, and the fine sediments are continuously entrained and redeposited.

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DISCUSSION

KRAY: My question is in reference to the wharf or pier which is free from sediments in Figure 11. What is the washout rate ahead of that pier? The sediments consist primarily of the cohesive soils, and I presume that washout and movement are very considerable along that face.

JOHNSON: You mean the scour? As far as I know, there are no problems. The penetration of the pile is such that the lower portion of the pile is never exposed.

KRAY: It doesn't extend too deep?

JOHNSON: No.

KRAY: Do you know by any chance what the foundation is of that particular pier?

JOHNSON: It is piles.

KRAY: Steel sheet piles?

JOHNSON: I am not sure of that.

KRAY: So there is a solid wall, at any rate?

JOHNSON: Right. The solid wall is preferable. It is a smooth wall and you don't get the high turbulence which is conducive to coalescence and deposition of the material.

RIEDEL: I would like to add a cautionary note to your suggestion that you won't have deposition along the base of the pier which is parallel to the main channel. I use as illustration what I called down in Vicksburg a couple of days ago a parking lot problem, sometimes referred to as a marine transportation problem, and it is. A ship is turning around in an anchorage, experiences some failures and runs into the ship which is tied up at the base of a pier very similar to the pier you spoke of, and the ensuing fire closes the port.

I would suggest that we have to be careful about the best solution for ease of maintenance; for example, docking along the base of a stream. Sometimes we must counsel ourselves on the safety problems as well as the advantages for maintenance of various solutions. I don't think we want to be moved too far in any one direction without a rationalization of all elements.

JOHNSON: Your point is well taken. In the particular case you refer to, there isn't any parking area in that main stream, and if you dredge a parking area from the mud flats, it will eventually fill up; nonetheless, I agree with your point.

BERTSCHE: Would knowledge of the whole hydraulic water flow of that area at the design stage help you in solving some of the sedimentation problems that occur? You pointed out the one flat that was essentially draining into the docking basin at the side. That is pretty obvious, perhaps it could be predicted by looking at the chart, but in more subtle cases, would a full, three-dimensional hydraulic model--either mathematical or full scale--aid in looking at the sedimentation, or is that part of the problem with the design process?

JOHNSON: Frankly, I don't think enough data exist for a remote area like that to build a model. The model can only be as good

as the prototype data. A new pier and expansion of this port have been proposed: the pier would be parallel to the stream along the mud bank.

BERTSCHE: Let me pursue this point. Would the sedimentation include a sand drop at the entrance? You were talking about transport down the coast. I would assume that as soon as it hits the breakwaters and jetties, it creates a problem.

JOHNSON: There are no breakwaters or jetties at that particular port, but at others, material does accumulate against the jetties. In my opinion, the rate is difficult to estimate unless there is a record of experience at nearby harbors. Santa Barbara, for instance, has a long period of record: in that vicinity, 250,000 to 280,000 cubic yards per year seems a reasonable expectation.

I think Bob Dean has worked at the Channel Islands Harbor further down the coast. What was the annual rate you estimated, and that dredging records show for that area?

DEAN: About a million cubic yards.

JOHNSON: So, there is quite a difference in a short distance between ports.

SAVILLE: The case of Channel Islands Harbor is interesting. The original design was based on Santa Barbara, and then upgraded to about 700,000 to a million cubic yards per year. Predicting sedimentation rates from past experience is a good practice, but you need present experience, too.

JOHNSON: That is correct. Between Santa Barbara and the Channel Islands Harbor, for example, is the Santa Clara River, which can get out of hand about every 25 to 30 years, suddenly dumping a huge amount of material just up the coast from the Channel Islands Harbor.

HERBICH: You mentioned some equations in the Shore Protection Manual that allow one to make estimates of sediment transport. Other equations have become available since that manual was published. What, in your opinion, is the accuracy of any estimate of sediment transport? Is it plus or minus 50 percent?

JOHNSON: It can be as much as 200 percent, and that is the basis of my concern.

TIDAL HYDRAULICS*

F. A. Herrmann, Jr.

Introduction

The branch of knowledge applicable to studies of the physical aspects of tidal waterways has become known as "tidal hydraulics." There is reason to regret the adoption of the term to include all tidal waterway engineering, as many are prone to consider its scope to be limited to the rise and fall of the water surface in consonance with the movements of heavenly bodies that generate the forces, and to the currents that are caused by the alternately rising and falling tide. It is emphasized that the term "tidal hydraulics" has come to be understood as including, in addition to the purely hydrodynamic considerations of such tidal waterways as inlets, estuaries, maritime straits, and canals, the following: channel dimensions and alignment; shoaling, including consideration of sources of the sediment, manner of transport, and cause of deposition; training works and dredging procedure (but not dredge design); jetty and breakwater layout; the salinity of the water, including associated phenomena; and the dispersal and flushing of pollutants. This paper, however, will concentrate primarily on salinity conditions.

Tidal phenomena occuring in any waterway seldom result from a single cause, but are more or less complex interactions of a number of factors. Thus, if a change in the regimen of a waterway is desired in order to effect an improvement, the change in each contributing factor and in the resulting interaction must be determined. The principal factors to be taken into consideration are: tides, tidal currents, freshwater discharge, salinity intrusion, volume of sediment, characteristics of beds and banks, wave action, littoral processes, and dispersal and flushing of pollutants.

*Much of the information presented in this paper was developed under the Civil Works Program of the U.S. Army Corps of Engineers. Permission granted by the Chief of Engineers to publish this information is appreciated.

Tides

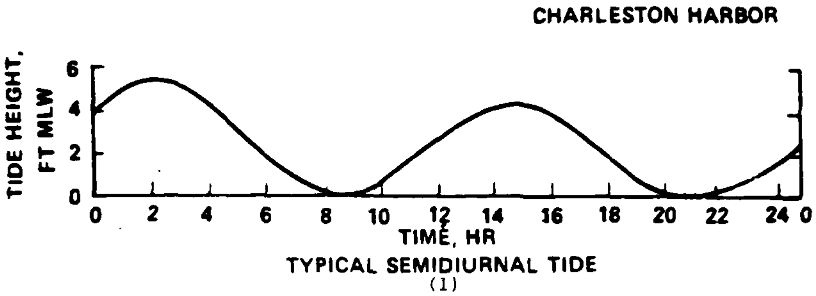
Tides are usually categorized as semidiurnal, mixed, or diurnal. Semidiurnal tides (Figure 1) are typical on the East Coast of the United States, and they exhibit two nearly equal tides (i.e., two nearly equal high waters and two nearly equal low waters) per lunar day (24 hr 50 min). Mixed tides (Figure 2) common to the West Coast exhibit two markedly different tides per lunar day. Along the Gulf Coast, one of the tides per day often vanishes, resulting in a diurnal tide (Figure 3).

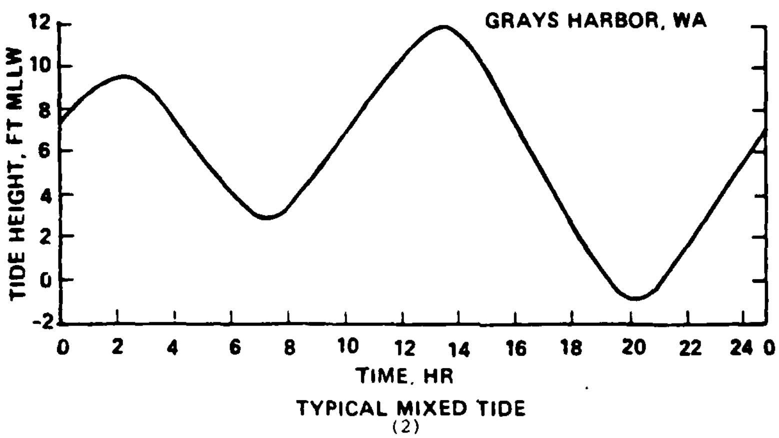
These tides generate an undulation in tidal waterways, and once started, it propagates upstream to some point where further progress is terminated by a barrier, or where the accumulating attrition causes the undulation to disappear. If the length of the estuary exceeds the length of the tide wave, as in the case of the Amazon River in South America, the system may contain two or more tides at the same time. Thus, the tide may be rising or falling in two or more reaches of the estuary at the same time. In some situations, the geometry of the waterway causes a stationary wave, but these cases are not so frequently encountered as the so-called progressive waves. Progressive waves travel upstream with a celerity related to water depth. Thus, during the propagation of a progressive wave, the high-water portions travel faster than the low-water portions of the wave, and this helps to distort the shape of the wave. As the wave progresses up the estuary, the duration of the rise decreases and the rate of rise increases; conversely, the duration of fall increases and the rate of fall decreases. The shape of a curve representing tidal heights plotted against time shifts from that approximating a sine or cosine curve to that exhibiting a quick rise of relatively short duration followed by a slow fall of relatively long duration.

Tidal conditions within a waterway depend basically on the exciting tide, the shape of the waterway, and the bottom friction. In a converging waterway, where friction is a secondary factor, tidal amplitude increases as the tidal wave progresses upstream. In diverging waterways, or those in which friction is more important than shape, tidal amplitude decreases as the wave progresses upstream. In addition, reflections can either increase or decrease the amplitude. Figure 4 shows the relative tidal amplitude along the Delaware estuary. Rapid convergence in the bay causes an increase in amplitude in the downstream area. In the next reach, the amplitude decreases, apparently from reflections from two large islands. In the upper reaches, convergence again causes the tidal amplitude to increase. Tidal range varies greatly throughout the U.S. The tide range in Gulf Coast estuaries is generally less than 2.0 feet, while tide ranges greater than 30 feet are common in Cook Inlet, Alaska.

Tidal Currents

As the tide wave progresses through a waterway, tidal currents are generated. Although a flood current basically occurs with a rising





Figures 1 and 2. Typical semidiurnal tide of East Coast (1), and typical mixed tide of West Coast (2).

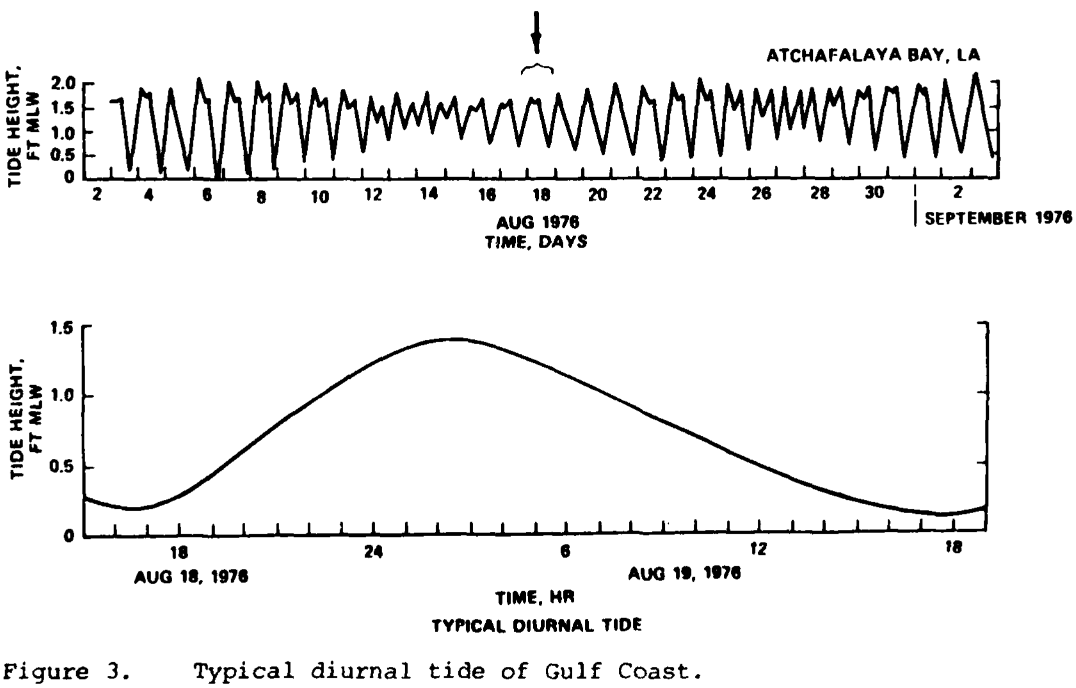


Figure 3. Typical diurnal tide of Gulf Coast.

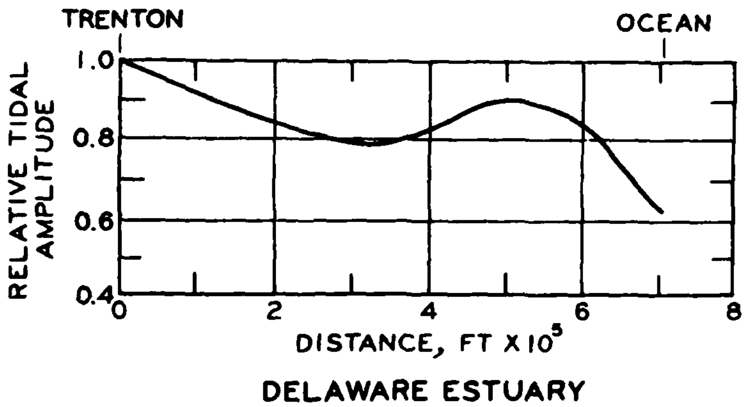


Figure 4. Tidal amplitude increases with convergence in Delaware Bay; decreases with reflection.

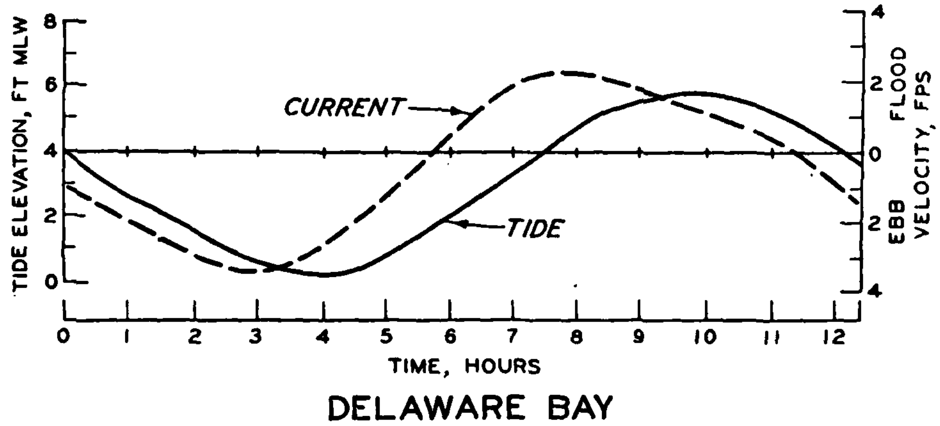


Figure 5. Typical tide-velocity relation.

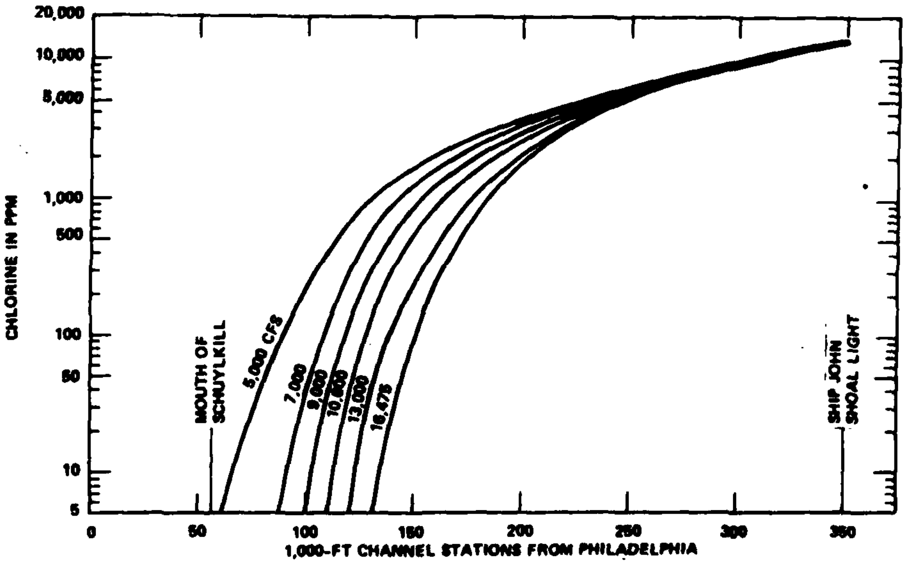


Figure 6. EFFECTS OF FRESH-WATER DISCHARGE ON BOTTOM SALINITY AT HIGH-WATER SLACK

MEAN TIDE

tide, there is generally a significant phase difference between the current and tide. The current flow will generally be in the "wrong" direction for an hour or two after the tide has changed. A typical tide-velocity relation is shown in Figure 5. Although low tide occurs at hr 4.0 in this example, the current continues to ebb until hr 5.5. Similarly, high water occurs at hr 10.0, but the corresponding slack current is delayed until hr 11.5. In general, the tidal currents in the lower portions of a tidal waterway will greatly exceed the magnitude of freshwater currents resulting from upland discharges.

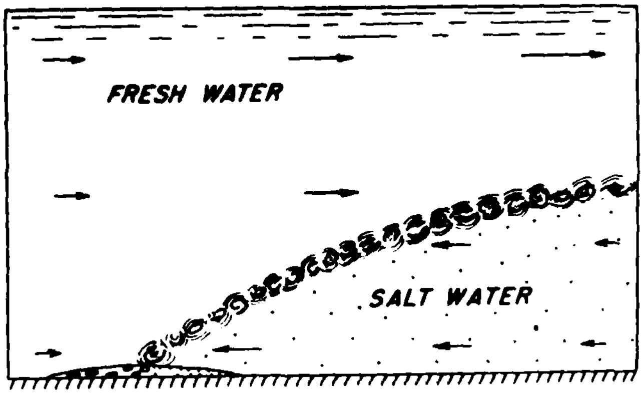
Freshwater Discharge

The freshwater discharges into the tidal waterway have profound effects on the regimen. They affect the basic tide independently of the effects of geometry, greatly modify the resultant current by lengthening the ebb and shortening the flood, transport upland sediment to the tidal waterway, and interact with salinity intrusion forces to produce density currents. Additionally, the inflow of fresh water is the means by which a tidal waterway purges itself of pollutants introduced by man, and variations in the freshwater discharge rate alter the extent of salinity intrusion, as shown for the Delaware estuary in Figure 6.

Salinity

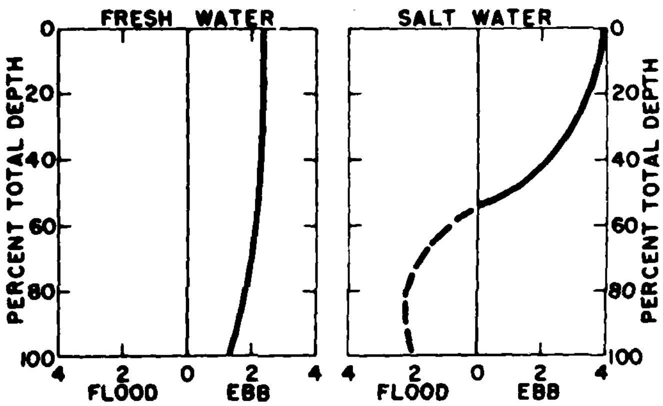
Engineers are interested in salinity conditions in an estuary for several reasons. As I will explain later, salinity intrusion can have a profound effect on the direction, magnitude, and duration of currents. Salinity also plays an important role in determining the sedimentation and circulation characteristics of an estuary. Government agencies and private concerns use water from estuaries for drinking water supplies, irrigation, and industrial purposes, and they are thus concerned with the possibility of saltwater contamination of their water sources. Salinity is also vital to the ecology of an estuary. The various fish and wildlife are tolerant to salinity in varying degrees. Thus, if salinity conditions were drastically altered, certain species might be driven out of the area. For these and other reasons, it is necessary to understand the significance of existing salinity conditions and be able to predict the changes in salinity conditions that might be brought about by some man-made change in the estuary.

Tidal action and freshwater discharge normally provide the primary mechanisms for mixing salt and fresh waters as a result of tidal currents. Salinity characteristics in real estuaries can be classified into three broad categories: highly stratified, partly mixed, and well mixed. In a highly stratified estuary, a distinct saltwater wedge will be present. In a well-mixed estuary, the salinity from surface to bottom will be essentially uniform. The partly mixed case falls in



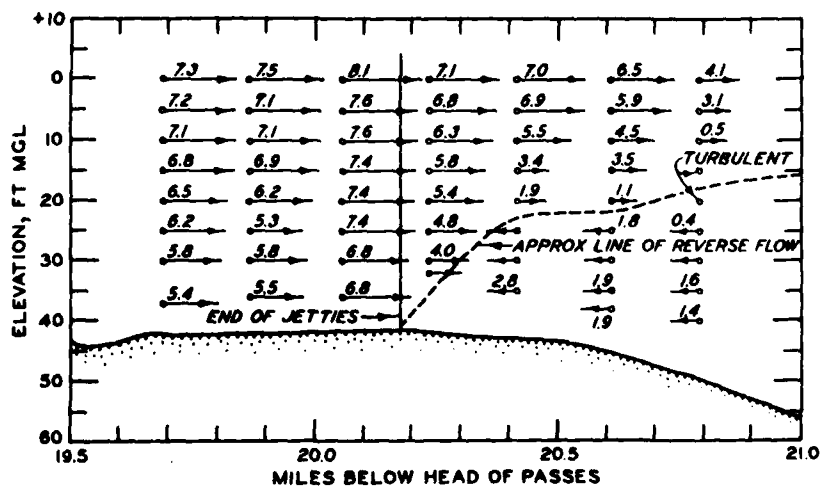
CONDITIONS TYPICAL OF
HIGHLY STRATIFIED ESTUARY

Figure 7.



TYPICAL DISTRIBUTION OF VELOCITY
IN HIGHLY STRATIFIED ESTUARY

Figure 8.



SOUTHWEST PASS
VELOCITY DISTRIBUTION
FRESH-WATER DISCHARGE 300,000 CFS

Figure 9.

between the other two, having a distinct vertical salinity gradient, but not a wedge.

In an ideal case of a highly stratified estuary, the freshwater velocity and the tidal currents are not great enough to create appreciable mixing of the salt and fresh waters, but the shear stress of the fresh water on the face of the saltwater wedge will cause a reversal of current direction within the saltwater wedge (Figure 7). The salt water moves upstream at the bottom of the wedge but downstream at the top of the wedge. In addition, the wedge will move upstream and downstream in phase with the tide. The extent to which the wedge intrudes upstream depends on the freshwater discharge, the channel depth, and the density difference between the fresh and sea waters.

Typical velocity distributions in a highly stratified estuary are shown in Figure 8. Upstream from the limit of saltwater intrusion, the direction of the current is the same at all depths, and since there is normally no reversal of flow by tidal action in a highly stratified estuary, the current direction is downstream at all times. In the region of saline intrusion, the direction of the current from the surface to somewhat below the salt-fresh water interface is downstream. However, that near the bottom is upstream to compensate for the salt water being lost from the interface by mixing and for the salt water flowing downstream within the wedge. Because there is virtually no mixing at the interface, the water above the interface has essentially zero salinity, while that below the interface is essentially seawater.

Southwest Pass of the Mississippi River is the best example of a highly stratified estuary. Figure 9 shows the velocity distribution (averaged over a tidal cycle) at the mouth of the Pass for a river discharge of about 750,000 cubic feet per second (cfs). Flow in the Southwest Pass was 300,000 cfs. The line of zero velocity is slightly below the interface. For this discharge, the tip of the saltwater wedge is located adjacent to the outer ends of the jetties. The upstream extent of saltwater penetration is dependent on the magnitude of the freshwater discharge, as shown in Figure 10. For an extremely low river discharge, the wedge intrudes upstream about 140 miles, which is upstream from New Orleans.

Whereas the highly stratified type of estuary was characterized by a two-layered system with zero salinity in the surface layer and sea salinity in the bottom layer, the well-mixed case is characterized by essentially uniform salinity from surface to bottom (Figure 11). The salinity at the entrance to the estuary is that of seawater; and it decreases with distance upstream from the entrance. Density currents in a well-mixed system are not completely eliminated, but they are much weaker than in a stratified system or than the tidal currents. There is a complete reversal of flow direction at all depths with the changing tide.

Velocity distributions typical of well-mixed estuaries are shown in Figure 12. The currents reverse with tidal phase throughout the estuary. In the fresh and brackish water regions, ebb currents at all depths predominate slightly over flood currents because of the freshwater discharge. In the intermediate and highly saline regions, however, the bottom flood currents usually predominate slightly over

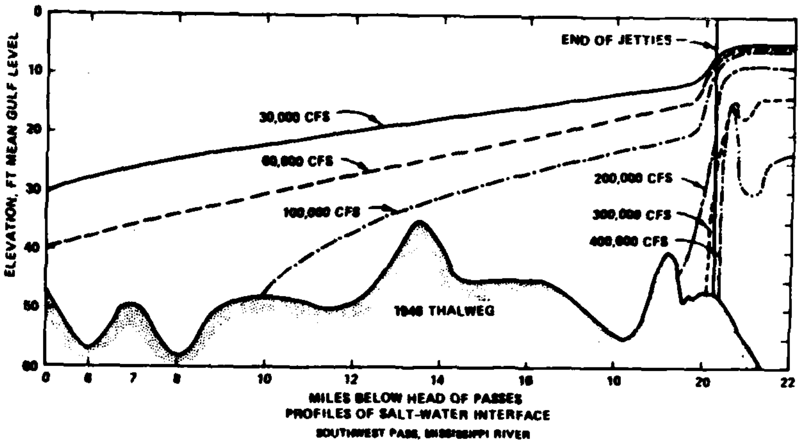


Figure 10. Freshwater discharge determines penetration of saltwater upstream.

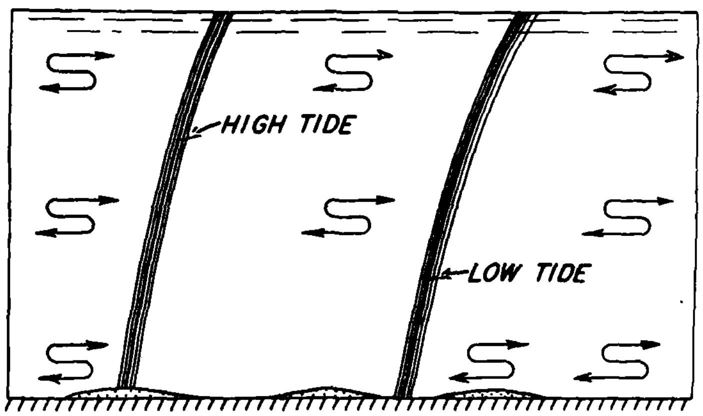
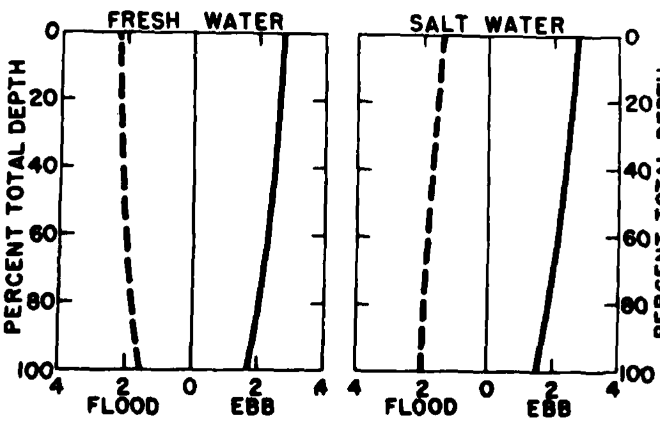
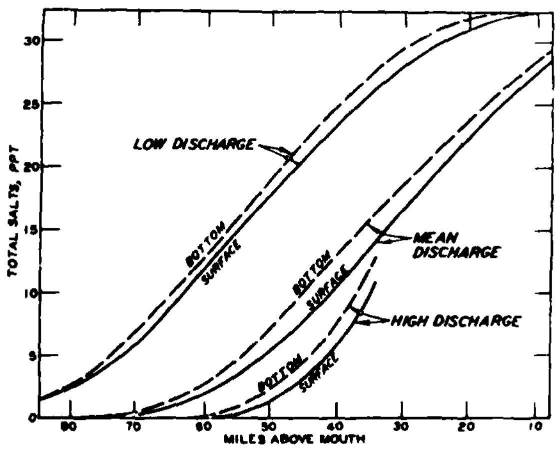


Figure 11. Conditions typical of well-mixed estuary.



TYPICAL DISTRIBUTION OF VELOCITY IN WELL MIXED ESTUARY

Figure 12.



SALINITY PROFILES - DELAWARE RIVER

Figure 13.

the bottom ebb currents. Salinities decrease more or less progressively from seawater at the entrance to fresh water in the upper reaches, and bottom salinities normally exceed those at the surface by 15 to 25 percent.

The Delaware River estuary is a typical example of a well-mixed system. Surface and bottom salinity profiles are shown in Figure 13, and it can be seen that there is essentially no vertical salinity gradient anywhere along the estuary. As in the highly stratified case, the upstream extent of saltwater intrusion is dependent on the freshwater inflow, as can be seen in Figure 13.

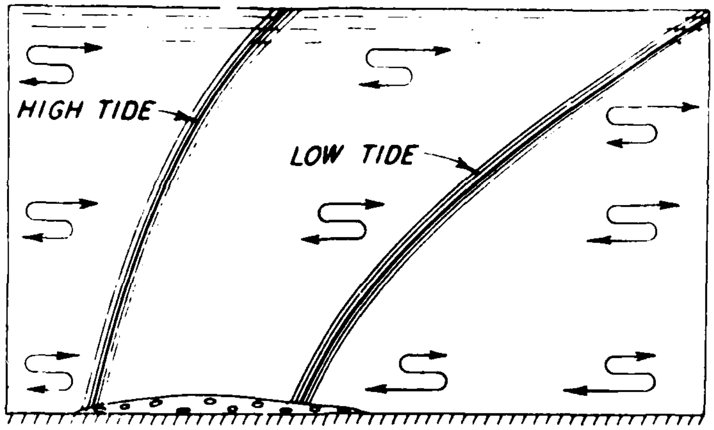
The partly mixed type is obviously an intermediate step between highly stratified and well mixed (Figure 14). The tidal mixing forces are great enough to break up the well-defined wedge, but not strong enough to effect complete mixing. The "interface" at high tide is considerably steeper than at low tide, and the "interface" moves over a considerable distance in the estuary with each tide.

As in the well-mixed case, there is a reversal of flow direction at all depths with the changing tide. When the current changes from flood to ebb, the reversal at all depths occurs almost simultaneously. However, when the current changes from ebb to flood in the lower portions of a partly mixed estuary, reversal at the bottom occurs as much as two hours before reversal at the surface. Thus, at the bottom, the duration of flood flow is usually greater than the duration of ebb flow.

In the region of the estuary just upstream from saltwater intrusion, the current at all depths reverses with tidal phase, and the vertical distribution of the current in either direction is similar to that in an upland river; the downstream current at all depths predominates over the upstream current because of the freshwater discharge (Figure 15). In the region of saltwater intrusion, the direction of the current both above and below the interface reverses with tidal phase. Above the interface, the net flow is downstream; below the interface, the net flow is upstream. The interface between the fresher water in the surface strata and the saltier water underneath is not so well defined as in the highly stratified type; however, the presence of the "interface" is often indicated by a discontinuity of either the vertical salinity profile or the vertical velocity profile.

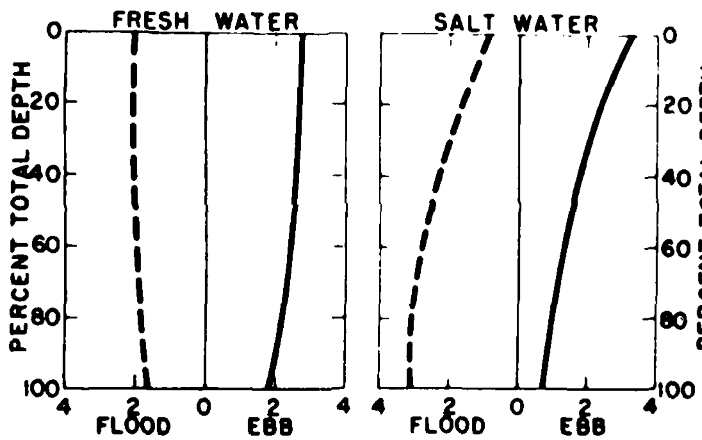
Savannah Harbor is an example of a partly mixed estuary. Typical salinity gradients at the entrance and about ten miles upstream are shown in Figure 16.

It was previously pointed out that the length of saltwater intrusion varies with the freshwater discharge. For any of the three mixing types, it has been found that an increase in freshwater discharge reduces the length of saltwater intrusion. However, the turbulent mixing generated by the tidal currents is more important than is the freshwater discharge. The Lower Mississippi River (highly stratified) and the Delaware River (well mixed) both have controlling depths of 40 ft. In the Mississippi River, a net downstream freshwater velocity of 0.83 feet per second (fps) results in an intrusion length of 125 miles for a river discharge of 128,000 cfs. On the other hand,



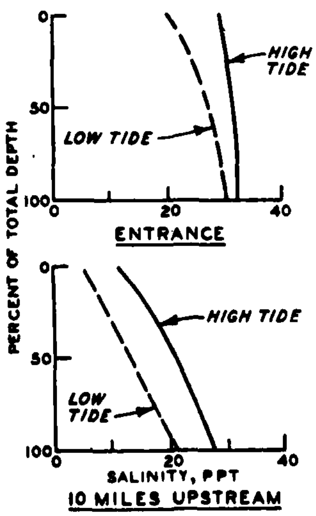
CONDITIONS TYPICAL OF
PARTLY MIXED ESTUARY

Figure 14.



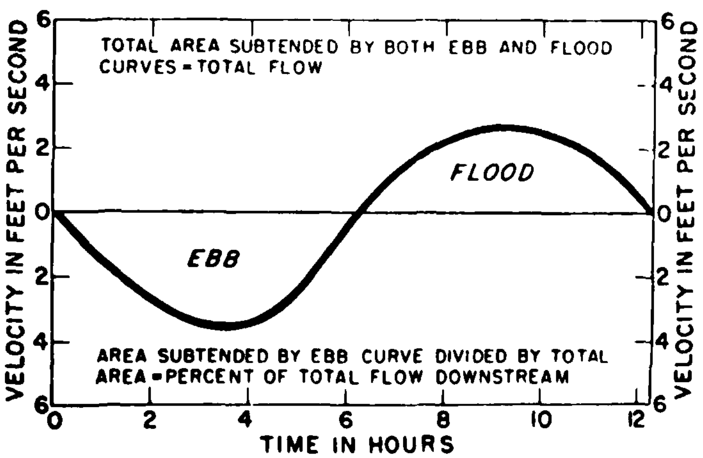
TYPICAL DISTRIBUTION OF VELOCITY
IN PARTLY MIXED ESTUARY

Figure 15.



SAVANNAH HARBOR

Figure 16.



COMPUTATION OF FLOW DISTRIBUTION

Figure 17.

in the Delaware River, a net downstream freshwater velocity of only 0.13 fps holds the intrusion length to 70 miles for a river discharge of 12,000 cfs. The Mississippi River is a very narrow estuary and has a tide range of only about 1-2 feet. It thus has a relatively small tidal prism. The Delaware, on the other hand, has a very broad bay and a tide range of 5-6 feet. It thus has a relatively large tidal prism.

Mixing

It has been found that the degree of mixing is generally a function of the ratio of the freshwater discharge over a tidal cycle to the tidal prism, where tidal prism is defined as the total volume of water entering the estuary from the sea during the flood (rising) tide. When the freshwater inflow is high compared to the tidal prism (ratio greater than about 0.8), the stratified condition results. When the opposite is true (ratio less than about 0.1), the well-mixed condition results. It should be noted, however, that the degree of mixing can be affected by several other factors such as wind, waves, ships, and turbulence at the mouths of tributaries and channel constrictions.

The freshwater discharge/tidal prism ratio is by no means an exact measure of the degree of mixing. It is not possible, for example, to define accurately the relative degree of mixing among estuaries having reasonably similar stratification conditions. Perhaps a more reliable parameter for defining the degree of stratification is the "estuary number" developed by Harleman and Ippen. The estuary number is defined as

$$\text{estuary number} = \frac{P_t F_o^{\,2}}{Q_f T}$$

where

P_t = tidal prism (the volume of seawater entering the estuary on the flood tide)

F_o = Froude number $= \frac{u_o}{\sqrt{gh}}$; u_o is the maximum flood tide velocity at the ocean entrance, and h is the mean depth of the estuary

Q_f = freshwater discharge

T = tidal period

The degree of stratification increases with decreasing value of the estuary number.

An estuary may be changed from highly stratified to partly mixed or well mixed by reduction of the freshwater discharge; conversely, one may be changed from well mixed or partly mixed to partly mixed or

highly stratified by increasing the freshwater discharge. Such a change can be effected by a long-term change in freshwater discharge resulting from upstream flow modification or by seasonal changes in freshwater discharge.

Minor changes in mixing types are being constantly effected by deepening, widening, lengthening, or other improvements to estuary channels for navigation. As channels are dredged deeper and deeper, the salt water penetrates farther into the estuary and the degree of vertical stratification of the fresh and salt water is increased because of increased tidal prism and reduced tidal current velocities.

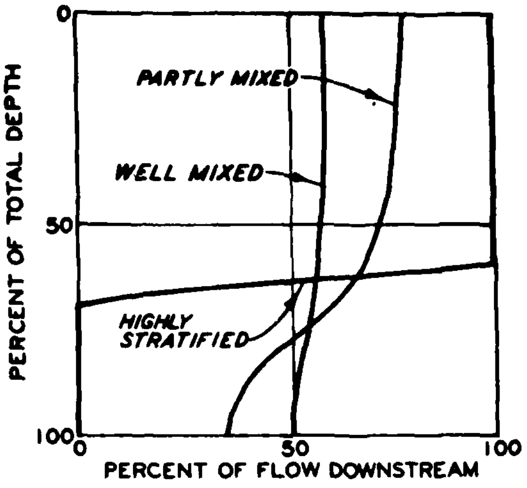
Flow Predominance

I now want to introduce the concept of flow predominance. This is a very useful concept for analyzing velocities, especially with respect to density currents. For this method, velocity observations are made at several depths at a given location, and the data are reduced to an expression which tells whether the predominant flow at each depth is upstream or downstream and in what percentage of the total flow at that point. A conventional plot of velocity vs. time is made for the observations at each point (Figure 17). The area subtended by the ebb curve is then divided by the sum of the ebb and flood curve areas. The result defines what percentage of the total flow per tidal cycle at that point is directed downstream, and is referred to as the ebb predominance.

At the bottom of a saltwater wedge, the flow predominance can be 100 percent upstream; while in the freshwater layer at the surface, it can be 100 percent downstream, as shown in Figure 18. Near the entrance of a well-mixed estuary, the flow predominance will be slightly upstream at the bottom, but more strongly downstream at the surface, as shown in Figure 18. Farther upstream, the flow predominance will be downstream throughout the entire depth. In a partly mixed estuary, upstream bottom predominance will be fairly strong at the entrance (Figure 18), and will extend a considerable distance upstream. Surface flow predominance will be strongly downstream throughout the estuary, except in areas under the influence of large-scale eddies.

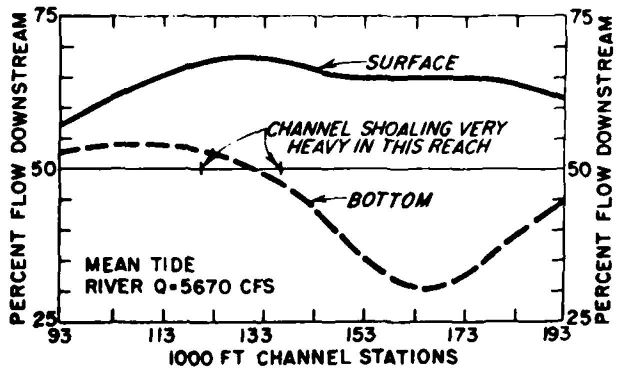
To obtain a broader impression of flow conditions in the estuary, it is possible to plot a profile of flow predominance along the estuary at various depths. That location along the channel at which the net flow is balanced (50 percent ebb) is called the null point. That is, there is no net flow in either direction. The surface and bottom flow predominance for Savannah Harbor are shown in Figure 19. The null point on the bottom for this freshwater discharge is located where the dashed line crosses the 50 percent downstream line.

An alternate means of determining time-average flow conditions at any point is referred to as velocity predominance. In this case, it is only necessary to determine the velocity at any point averaged over a complete tidal cycle. The result is then "nondimensionalized" by dividing by the freshwater velocity. An advantage of the velocity



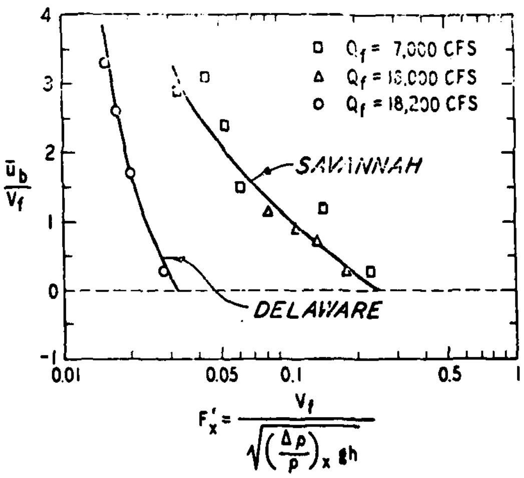
TYPICAL FLOW PREDOMINANCES

Figure 18.



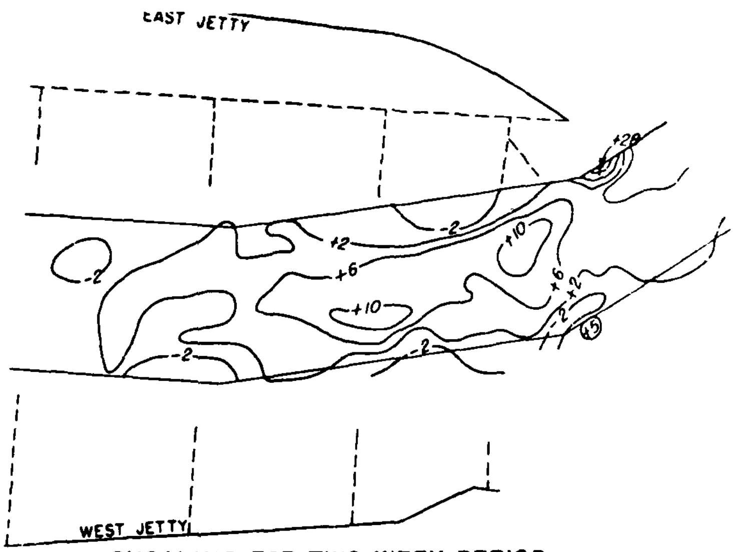
RELATION BETWEEN NORMAL SURFACE AND BOTTOM FLOW IN SAVANNAH HARBOR

Figure 19.



BOTTOM VELOCITY CORRELATION

Figure 20.



SHOALING FOR TWO-WEEK PERIOD SOUTHWEST PASS, MISS. RIVER

Figure 21.

LOCATION MAP SAVANNAH HARBOR

Figure 22.

predominance method is that it appears to have a unique correlation with the local densimetric Froude number for a given estuary, as shown in Figure 20. It appears that this correlation is not affected by changes in freshwater discharge, tidal amplitude, or channel depth. Thus, it should be possible to predict the position of the bottom null point for various discharges or depths.

Salinity Effects on Shoaling

Saltwater intrusion plays an important role in estuarine sedimentation. First, the salt water probably causes flocculation of suspended clays, which prevents them from being carried to sea in the upper flow layer. Second, density currents can move sediments upstream along the bottom to the vicinity of the flow predominance null point.

For highly stratified estuaries, rapid shoaling will be experienced at the tip of the saltwater wedge. As mentioned before, the tip of the saltwater wedge at Southwest Pass is located at the outer end of the jetties for a discharge in the pass of about 300,000 cfs. The shoaling pattern developed in a two-week period with a freshwater discharge varying from 248,000 to 294,000 cfs is shown in Figure 21. The shoaling does indeed bracket the tip of the saltwater wedge. Note that the maximum change in depth was 28 feet.

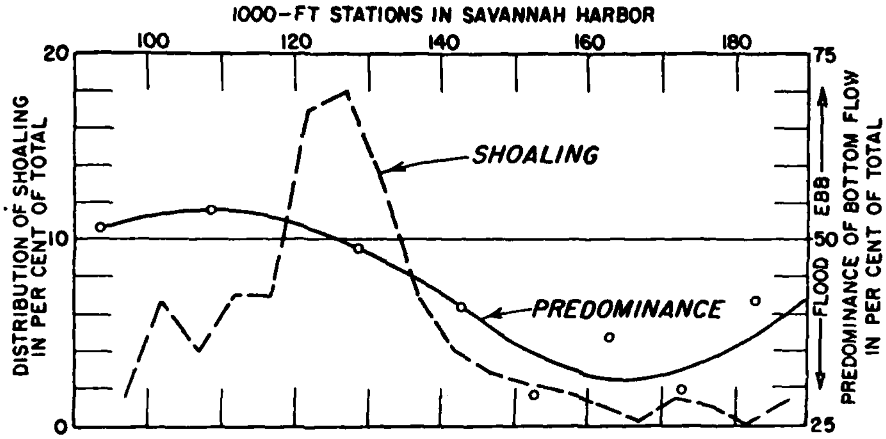
In partly mixed estuaries, the flow predominance null point usually is an area of heavy shoaling. In well-mixed estuaries, however, that is not usually the case, since density currents are quite weak.

Savannah Harbor

Savannah Harbor (Figure 22) is an excellent example of a partly mixed estuary. More than 75 percent of the flow is carried through Front River and North Channel. The relation between the bottom flow predominance and the shoaling rate in the navigation channel is shown quite dramatically in Figure 23. Of an annual shoaling of roughly seven million cubic yards, more than two-thirds occurs in the six-mile reach which brackets the bottom flow predominance null point.

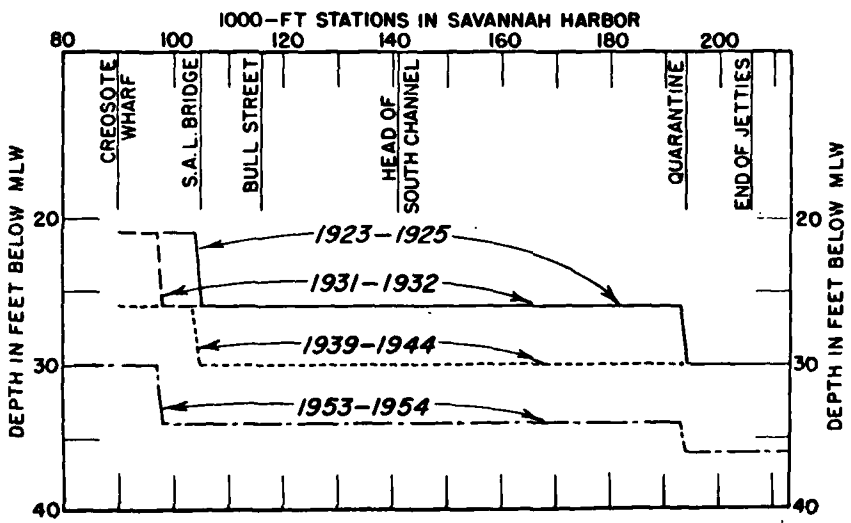
Savannah Harbor also gives a striking example of the effects of increasing channel depth on shoaling. The navigation channel has been progressively dredged from 26 feet in 1889 to its present depth of 36 and 34 feet. Profiles of the various channels are shown in Figure 24. Reliable dredging records are available for the periods indicated in the figure. For purposes of analysis, the navigation channel was divided into thirds, and the average annual shoaling rate was determined for each of the four time periods for each channel section (Figure 25).

The shoaling rate in the downstream third has decreased steadily, so that almost no dredging is now required. In the central third, the shoaling rate increased rapidly until the present channel was constructed, then it decreased significantly. The upstream third shows a very rapid increase in shoaling. By examining these data, we can



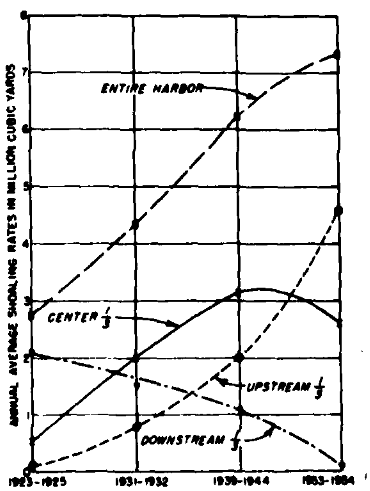
RELATIONSHIP OF SHOALING AND PREDOMINANCE OF BOTTOM FLOW

Figure 23.



PAST AND PRESENT CHANNEL DEPTHS

Figure 24.



PAST AND PRESENT SHOALING CHARACTERISTICS OF SAVANNAH HARBOR

Figure 25.

follow the upstream migration of the zone of primary shoaling and, by implication, the null point of the bottom flow predominance. The upper dashed line in Figure 25 shows that the harbor-wide shoaling rate increased essentially linearly until the final and most drastic deepening was effected. In this final period, harbor-wide shoaling exhibited a much smaller increase than for the previous channel deepenings. This indicates that by the time of the final deepening, density effects in the harbor had developed to such a degree that almost all potential shoaling material was trapped within the harbor. Thus, there was an upstream shift in the region of heaviest shoaling but relatively little increase in the total volume of annual shoaling.

The early upstream migration of the major shoal area was not a significant problem because disposal areas for dredged material from earlier dredging operations were readily available. In the last time period, however, the region of major shoaling was in the port area, where disposal areas are not readily accessible. Those that are available are rapidly being filled. Thus, in addition to greatly increasing the volume of material that must be dredged, the enlarged channel shifted the location of the shoaling to an area where disposal of the dredged material is increasingly difficult and expensive. Such a change in maintenance operations and costs should be identified in the design process to enable determination of overall project costs and potential environmental problems.

DISCUSSION

WEBSTER: Have you investigated what forces act on the ships, or how ships maneuver when the current is going one way on the surface and another way below?

HERRMANN: No, we haven't. In the reports of some investigations, we have noted areas where these types of currents seem particularly severe. We communicate the results to the field offices doing the design work. I am not sure whether they take that sort of thing into account, but it certainly could be a problem.

SEARLE: Based upon a lot of experience finding and raising ships on the bottom of the ocean, I believe current curves that are plotted over a tidal cycle are useless. You have to plot the tidal current in the vertical column across the full lunar cycle. I can cite you several examples. A salvage operation we are now engaged in, for example, in Newfoundland: at one end of the tidal cycle, you get a reversal of the current. To me, supervising divers on the bottom, reversal of the current means that I get zero current for perhaps 5 minutes or 10 minutes or 30 minutes: I get a low-current window.

At other parts of the tidal cycle, the lunar cycle, there is no reversal in some places in the world. If you need to know the forces exerted by currents on a ship, you must know the tidal stage and the lunar cycle stage.

HERRMANN: This has other implications. We have a model of the Chesapeake Bay and during this past year, I guess it was, we were asked if we could help to locate some barges that had sunk. The Coast Guard was concentrating its efforts downstream from the location where they sank. With our knowledge of what the currents were in that area, we said, the predominance of flow in the bottom is upstream. Go upstream and look for them. They found them upstream.

SEARLE: Yes, I can cite you cases of looking for a sunken barge. If you look for it at a particular time in the tidal cycle, you will find it. At another part of the lunar cycle, you won't find it.

WAVES AT PORTS AND HARBORS*

C. L. Vincent

Introduction

Estimation of short-period (1 to 30 second) waves in the vicinity of ports and harbors can be made difficult by the same features of the physical environment that make the site desirable for port development. Ports are often located in areas with shallow and highly irregular bathymetry. Additionally, the shoreline or harbor configuration may be geometrically complex, and there may be strong tidal or riverine currents. As a result, practically all the simplifying assumptions used to make wave calculations tractable do not hold.

In this presentation, I wish to discuss the state of the art in estimating wave conditions in port areas, and direct your attention to areas where work is needed. I wish to emphasize two areas: developing a wave climate and modeling waves. I will cite a few papers, but this presentation is not intended to be a review of the subject. Further, it must be clear that the solution of the wave problem depends heavily on knowledge of the water level, currents, and bathymetry.

Developing a Wave Climate

For the purpose of port design, it is necessary to know the general wave climate of the area. For the purposes of modeling, it is desirable to have information not only on wave heights and periods but wave directions as well. The data should be climatological and they should contain information on extremes and information on the day-to-day wave climate. Information on long-term climate variations may be helpful if sediment transport problems are to be addressed. Information on wave grouping is desirable as well. Two questions require attention. First, how does one obtain the basic data, and second, how does one statistically treat quantities such as directional spectral characteristics?

*This summary is based on research performed under the coastal engineering program of the U.S. Army Corps of Engineers. Permission to publish this information is appreciated.

It is helpful to start the discussion by looking at how wave data can be obtained in the region of the harbor. In general, there is very little one-dimensional wave data available on which to base a wave climate, and almost no directional data. Either an extensive gaging program extending ten to twenty years must be established, or the designer must go to a synthetic climate obtained through hindcast techniques. In the deep water case, significant progress has been made in the development of hindcast models, especially in predicting spectral characteristics. Several models are listed in Table 1. In applications involving large storms, the root mean square (RMS) error in prediction is of the order of 1 meter, which is generally satisfactory for climate estimates of extremes. These models require very large computers. A major limitation in the application of the models is lack of knowledge of the meteorology, particularly on the oceanic scale.

The next stage, if simulations must be used, is to begin modeling wave growth, transformation, and decay in shallow water. Modeling may be needed even if some gage data are available. If the bathymetry is complex, or if strong currents are present, gage data tends to be site-specific and not readily extrapolated or interpolated. These modeling problems will be discussed in the next section.

Although the limitations of gaging need to be recognized, significant advances have been made in instrumentation to make it reliable and reasonable in cost. Remote sensing techniques can also be very useful. The example of side-looking imaging radar given in Figure 1 shows in great detail patterns of refraction, diffraction, and breaking. Many of these instruments can operate in poor weather conditions, and can give a designer an improved picture of wave activity in the port area. Because the bathymetry may be complex and the wave field irregular, data from remote sensing systems may be useful in deciding where to place gages and in interpreting gage results.

The data synthetically produced by hindcast models or measured directly by gaging programs can provide the wealth of data required to understand waves at ports and harbor entrances. The data extend beyond providing just significant wave heights and periods to aspects of directionality and grouping. It is not yet clear what methods are best for statistically analyzing and displaying these data. Indeed, such questions as definition of a design spectrum are not uniformly answered.

Modeling Techniques

Two classes of methods for modeling wave problems will be discussed: numerical and physical modeling. The advantages and disadvantages are presented. It is essential to remember that both methods entail simulations in which a large number of simplifications are made.

The primary causes of the difficulties in numerical modeling of waves lie in the irregularity of the bathymetry, the presence of currents, and nonlinearities of the waves. One problem is the

Figure 1. Waves on Ebb Jet, at the mouth of the [illegible] SLAR (side-looking airborne radar) image provided by [illegible] State National Guard Remote Sensing Group.

TABLE 1 SOME DEEP WATER SPECTRAL PREDICTION MODELS

DEVELOPER/REFERENCE	PRIMARY USE	PUBLISHED ERROR CHARACTERISTICS (in hindcast mode)
Fleet Numerical Oceanographic Center	Ocean	up to 3 m
Salfi (1974)		
Waterways Experiment Station		
Resio and Vincent (1977)	Lakes	0.5 m
Resio and Vincent (1979)	Ocean	1.5 m
Cardone et al (1975)	Hurricane	1.5 m
Hybrid parametric	North Sea	0.9 m
Gunther et al (1979)		

refraction-diffraction of waves. Almost all practical numerical models of waves require that the rate of change of bottom slope be small with respect to the wave length. Even if this constraint is only mildy violated, the modeling of the bathymetry requires a dense grid mesh, thereby creating a large computation problem. In deep water, the effects of nonlinearities appear significant in determining wave growth. Research underway by Heterich and Hasselmann suggests that these nonlinearities are also important in shallow water, which if correct, complicates spectral modeling, requiring cross-spectral transfers. One final, and so far intractable, problem is improved treatment of wave breaking.

Two approaches to the numerical modeling of waves in shallow water are now used. The first is the spectral approach. There are several models available that treat this problem (Table 2). The Hsaio model allows intraspectral energy transfers; Wang and Yang allows currents; none treats diffraction. The advantage of the spectral techniques is that they consider the entire wave spectrum, and can treat the effects of refraction of each wave component. One disadvantage occurs largely because this type of modeling is still under development and the refraction part of the algorithm is normally primitive. A second disadvantage is that the algorithm is complicated, and can require large amounts of computer storage and run time.

The second type of numerical model normally is used to treat only one wave component. In this class, four types are available: ray, finite differences, finite element, and Boussinesq finite difference models. Examples are provided in Table 3. Both ray and finite differences models based on linear refraction theory are reasonably well known and are used in standard engineering design worldwide. The most significant problem with these models is that they do not treat

TABLE 2 SOME SHALLOW-WATER SPECTRAL MODELS

DEVELOPER/REFERENCE	MECHANISMS INCLUDED
Collins and Weir (1972)	Wave growth, refraction shoaling, bottom friction
Hsaio (1978)	Wave growth, refraction, shoaling, various bottom interaction terms
Wang and Yang (1977)	Refraction, shoaling

TABLE 3 SOME REGULAR WAVE PREDICTION MODELS

DEVELOPER/REFERENCE	TYPE
Birkemeier and Dalrymple (1975)	Finite difference linear refraction, currents
Poole et al (1977)	Linear refraction, rays
Berkhoff (1972)	Finite element refraction - diffraction
Houston (1980)	Finite element refraction - diffraction
Abbott et al (1978)	Finite difference, refraction - diffraction and amplitude effects (Boussinesq terms)

diffraction, and in areas of irregular bathymetry can give misleading answers. Breaking is normally treated with a depth-limiting criterion.

The other two types of models do handle aspects of the refraction-diffraction problem. In the Boussinesq approach of Abbott, the equations treat effects of amplitude on dispersion as well as refraction and diffraction. The finite element models are based on linear theory, but more effectively handle irregular geometries and reflected waves than the Boussinesq model. The finite element models are steady-state models, while the Boussinesq-type model is a time-marching scheme. The advantage of both techniques is that they provide a more accurate model of the waves. The disadvantage is cost. These models require grid mesh or element sizes of the order of one-tenth the wave length. At this time, their use appears justified for small areas or for large

areas when just a few cases are run. The incorporation of current effects has not been widely explored. An ideal numerical model would provide the effects of amplitude, as in the Boussinesq model, handle boundaries and reflected waves with the ease of the finite element models, but use a telescoped grid mesh that would allow large grid-mesh values in areas of least interest. Unfortunately, such a model does not yet exist.

The other major approach to investigating waves at port entrances is the use of an undistorted physical model based on a Froude scaling law. These models by their nature handle the refraction-diffraction and nonlinear problems through scale modeling. Currents may also be included. Breaking occurs naturally as well, although it is not clear that wave reformation and wave-energy dissipation are correctly modeled. In any case, this model's estimates are probably closer than those of any numerical model.

Areas in which physical modeling could be improved are through the use of irregular waves with a directional spread, and simulation of wave grouping. If conditions that include significant breaking are modeled, model verification studies should possibly be encouraged. The major disadvantages of the physical model are its cost and the time required for construction and testing. In the case of large harbors, however, there is little other choice.

Summary

The advent of numercial models and improved instrumentation should lead to an improvement in our ability to estimate wave conditions in port and harbor entrances; however, for many problems, a physical model appears the most effective solution. Research is required to extend the applicability of numerical models and to develop more economical solution techniques. Research is also required to improve simulation of irregular waves in physical models.

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DISCUSSION

WEBSTER: Do you have instrumentation to measure directional spectra? How do you do that?

VINCENT: There are instruments that give measures of the directional spectrum. We have current meters, horizontal current meters, and pressure transducers. There are any number of arrays that will give you some measure of the directionality of the sea. There are pitch-roll buoys, and radar techniques. The major difficulty with these techniques seems to be that they really--from the input we get back--don't give, in many instances, a narrow enough idea of what the wave direction is. Most of these techniques tend to spread out the directionality. There is some debate about whether the spread is real or an artifact of the algorithm used to generate the spectrum.

The remote sensing data tend to show much narrower spread. So, we can get ideas of mean directions in part of the spectrum reasonably well, but if you need to know the very narrowness of the spread, and perhaps even the wave direction to just a few degrees, it

may not be possible at this time. We can certainly give you a general idea of the direction from which the waves are coming.

WEBSTER: Can I follow that up? Does your hindcasting model give directional information? Other than the direction of the principal waves, will it give an idea of the spread?

VINCENT: The models I discussed--all but one--calculate for each frequency how much energy is going in as many as 16 or 24 different directions. The problem is that normally the wind information may not be good enough to justify finer directionality, although the models would allow it. So, with any one frequency component you can go to 16 or 24 points of the compass and have an estimate of how much energy is going in each of those directions and get a truly directional spectrum.

DEAN: One of the types of waves you didn't mention that can be of interest to the port designer is the second-order-of-force waves driven by groups of waves. Would any of the methods you mentioned, say, Abbott's model, if given a group of waves to deep water, also represent these?

VINCENT: Abbott's model is really the only one, I think, that has the potential to do that. Again, it is limited by an Ursell parameter. You can put an irregular wave train in Abbott's model. The only difficulty that you have is that of specifying the boundary conditions. Abbott claims that you should be able to derive that from his results. As far as I know, no one has checked this.

THE IMPORTANCE OF CONSIDERING ENVIRONMENTAL EFFECTS IN THE DESIGN OF ENTRANCES TO PORTS AND HARBORS

Scott McCreary

The Conservation Foundation is principally a research and communication organization. We are often engaged to carry out case studies, and from these we make recommendations for various agencies and research organizations. I would like to take a similar line in this presentation, reviewing a number of case studies undertaken to inform and promote the integrated management of estuaries and wetlands.

I want to suggest that at least one important dimension of port planning is the fact that the environmental consequences are a local planning issue, and one that should receive attention in the context of other important dimensions.

The Ballona Wetlands

An interesting case study is the history of the Ballona wetlands, located in an unincorporated area of Orange County, California. The Ranch of Ballona, at the time some 14,000 acres in size, is outlined on an 1888 map of California in Figure 1. It included about 2000 acres of what were then called Class-4 lands, which means lands inundated by tidal action, or mostly wetlands and estuaries. In 1896, the marshland in this area extended to the Santa Monica Branch of the Santa Fe Railroad (as indicated in Figure 1). In 1934, a project was undertaken to straighten and channelize the upper portion of Ballona Creek, but seaward of this project, the natural wetlands were still intact. Between 1930 and 1950, a number of oil rigs were located in the wetland area, as were a number of roads, as illustrated in Figure 2.

More dramatic changes occurred in the early 1960s with the construction of Marina del Rey. Figure 3 shows the first appearance of Marina del Rey on a map made in 1962. An overview of the area as it appears today (Figure 4) indicates the course of the Ballona Creek Channel.

Most of the wetlands remaining outside the boundaries of Marina del Rey are the property of the Summa Corporation, a division of Signal Oil Company. Of the original 2000 acres of wetlands, 120 acres are still what we might consider well-functioning and productive (Figure 5). About 180 acres along the fringes of these areas are converted wetlands

Figure 1. Ranch of Ballona, 1888.

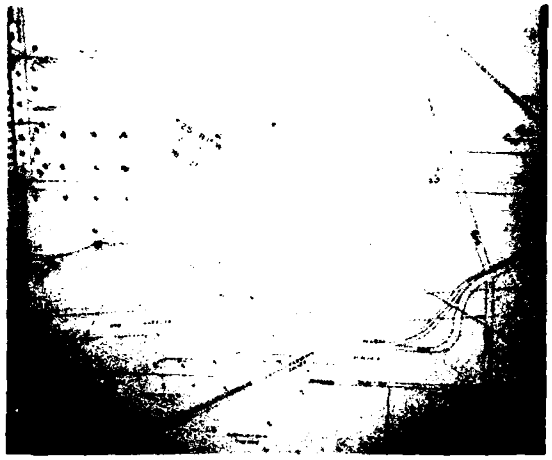

Figure 2. Oil rigs and roads in Ballona wetlands, 19[illegible]-1950.

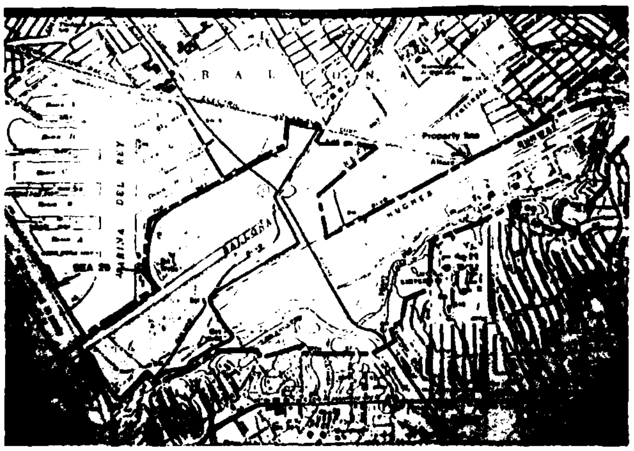

Figure 3. Construction of Marina del Rey in early 1960s.

Figure 4. Ballona wetlands today.

Figure 5. About 120 acres of original 2000 remain productive, well-functioning wetlands.

that could easily be used for tidal action, but 215 acres along the edges could be restored to wetlands only with great difficulty.

The alteration of the wetlands resulting from diking and filling for agricultural use and the construction of Marina del Rey left 120 acres of functioning wetland of the original 2000 acres, a rather substantial effect. Figure 6 illustrates the area. Obviously, this area could only be restored with a major public works project that would itself affect the environment, and that would likely be costly. The County of Los Angeles has expressed some interest in restoring portions of the Marina del Rey area and the Ballona Wetland to tidal action. The county's local plans allow for designation of special ecological areas, and this designation has been proposed for the area.

The proposal is incorporated in current efforts to carry out coastal plans in the Marina del Rey and Ballona wetland area. In 1972, the voters of the State of California enacted an initiative for coastal planning. This initiative produced the Coastal Act, passed by the California legislature in 1976. The act calls on local units of government to prepare coastal programs for their jurisdiction addressing the policies of the Coastal Act.

The major port districts are also required to draw up local coastal programs, taking into account issues of environmentally sensitive habitats, public access, and effects on nearby housing opportunities. The effect of this legislation has been to broaden consideration of port development beyond the design of the works themselves to take some of other larger planning issues into account.

Marina del Rey is pictured in Figure 7. It is one of the largest marina facilities in southern California. I want to point out that Marina del Rey and the conversion of other components of the Ballona system is not an isolated event in California. Prior to the enactment of the coastal initiative in 1972, approximately 102,000 acres of wetlands and estuaries were removed from the original 197,000 acres of marshes, mud flats, bays, lagoons, sloughs, and estuaries. Of the remaining estuaries, 62 percent have been subjected to severe damage, 19 percent have suffered moderate damage, and in southern California alone, 75 percent of the wetlands have been destroyed. I do not imply that these alterations result from port construction, of course. The important point is that the history of wetland alteration must be taken into account when new port facilities are designed. There are few wetland resources left, especially in heavily populated areas. The intense pressures of urbanization are patent in Figure 8, an overview of the entire Ballona area.

An organization known as Friends of Ballona, a citizens' group based in Los Angeles, has been working with the California Coastal Commission to try to bring about restoration of Ballona Lagoon. Those efforts have stalled. The local government was to have completed a plan by the end of the year, but has only just completed the work program.

The Summa Corporation is contending in court that the work program gives inadequate attention to the potential for industrial development in this area.

Figure 6. Heavily used areas of Ballona wetlands.

Figure 7. Marina del Rey.

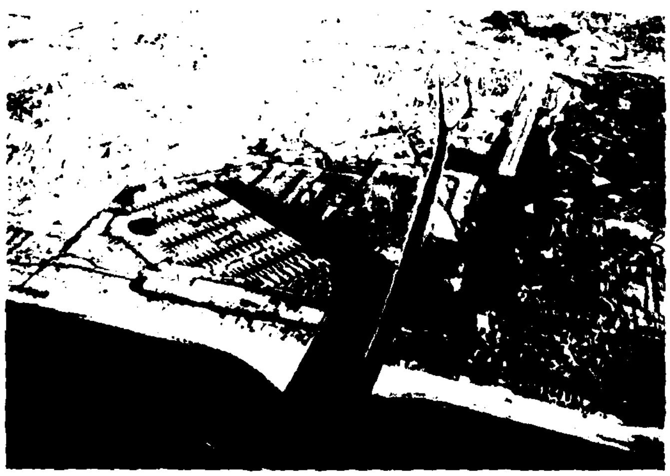

Figure 8. Overview of Ballona area.

The Conservation Foundation has recommended that the entire wetland area be restored. We have made proposals that go beyond the designation of a special ecological area suggested by Los Angeles County; we called for the restoration program to address the entire ecological unit. The fate of both proposals is suspended until the local coastal program is completed.

Beach Erosion

The waterfront of Charleston, South Carolina, is one of the Atlantic's largest ports, and clearly the hub of South Carolina's economy. In the 1930s, the port was protected by jetties. The construction work was preceded by an Army Corps of Engineers study, "Charleston Harbor Jetties," stating that jetties usually affect neighboring shorelines above and below the harbor project itself for about a mile. The effects are often greater. Figure 9 shows Folly Beach, South Carolina, one of a dozen barrier islands in the Carolina low country along the waterfront of Charleston County. It is the second island south of the entrance channel to Charleston Harbor, six miles away. Unlike Kiawa and Seabrook Islands, it is predominantly available to the public, and as Figure 9 indicates, there is public use of the beaches.

The problem at Folly Beach is the erosion occuring at least since records were first kept in 1849. This erosion has been exacerbated by efforts to protect the harbor facility around Charleston. In Figure 10, the stairway down from the sea wall has lost a bit of its footing, but this is a rather minor problem compared to others that we see in this area.

A number of attempts have been made to counteract the processes of erosion and beach recession, but the U.S. Army Corps of Engineers has concluded that had there been no efforts to control the erosion at Folly Beach, the condition of the beach in the future would be essentially the same as it has been in the past. Essentially, the reflective character of shoreline structures has furthered erosion on Folly Island.

The graph in Figure 11 charts the substantial shoreline recession on Folly Island between 1849 and 1977. Approximately 560 acres of beach front have been lost from Folly Island since 1849, at an annual rate of about 5.9 feet a year.

Erosion rates have accelerated in recent years. Along the reach illustrated in Figure 12, the erosion rate is close to 20 feet a year. The area is in Bird Key, on the end of Folly Island. The Corps has proposed a program to restore Folly Island. In addition, citizens have solicited the assistance of the Conservation Foundation and Coastal Plains Regional Commission to develop a comprehensive plan for the shoreline.

Figure 9. Public beach on barrier island, Folly Beach, South Carolina.

Figure 10. Erosion at Folly Beach.

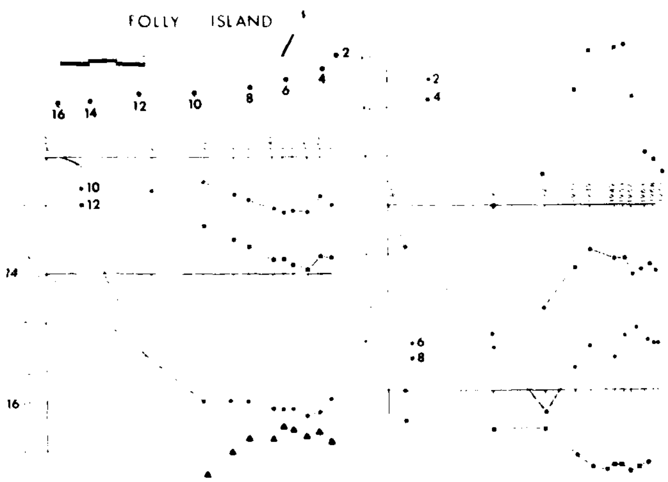

Figure 11. Shoreline recession at Folly Beach.

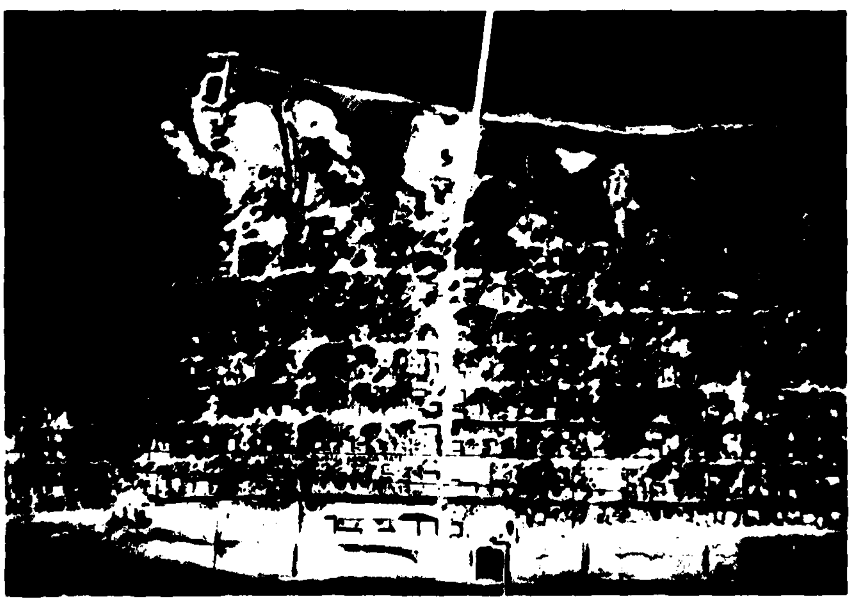

Figure 12. Erosion at Bird Key, end of Folly Island.

Estuarine Systems

The next case which I would like to consider briefly is that of the White Oak River in North Carolina, an estuary near Swansboro (Figure 13). In earlier days, the Swansboro River discharged through the area. The causeway built for Highway 24 now occupies much of the inlet in Bogue Banks.

The first major alteration to this area was the construction of the causeway itself. The original river extended approximately to the point marked. The second major modification is the Intracoastal Waterway.

Water now flows east and west through the waterway rather than toward the ocean through the inlet, as it did previously. The arrows in Figure 13 indicate spoil islands in the Swansboro-White Oak estuary. It is thought the spoil islands themselves may be contributing to rapid shoaling and sedimentation of the upriver areas. That, of course, has not been proved, but it is an opinion that is widely held by people in the Swansboro area.

Although the southeast bridge no longer crosses a usable channel, the northwest clearance is still passable by very small pleasure craft. There have been some very interesting side effects that are thought to be associated with the combination of the causeway construction, the construction of the Intracoastal Waterway, and dredge spoil disposal.

Particularly hard hit has been the oyster fishery, which was never important commercially, but has always been important to the local population. It is thought that siltation and sedimentation have covered some of the oyster beds, and in areas of low turbidity, the oysters are stunted.

One hypothesis is that the water temperature in the estuary has been lowered as a result of the rapid sedimentation and siltation. Another factor is that there is a rather sharp salinity gradient in the White Oak estuary. We find a range from 32 parts per thousand to 0 parts per thousand within just five miles. A curious aspect is that salinity is optimal for oyster growth at beds of stunted oysters. No one knows exactly what causes the stunted oysters.

Similar problems have been reported by the long-term residents of the area involved in crabbing, shrimping, and mullet operations. Local citizens have been attempting to get the Corps of Engineers to take action on what they consider to be the cause of some of these problems, but the causes have not been unambiguously identified.

The Isaak Walton League has become concerned with the problems of this area, bringing them to the attention of Congress. A meeting was convened with an environmental mediator in which an agreement was reached between the towns and county, the Isaak Walton League, and local fishermen to designate representatives for an advisory council to work with the Corps.

The concept of environmental mediation is a relatively new one borrowed from labor arbitration. The idea is that in environmental disputes of several parties, those parties with a genuine stake in the outcome should be encouraged to sit down at the table together, to

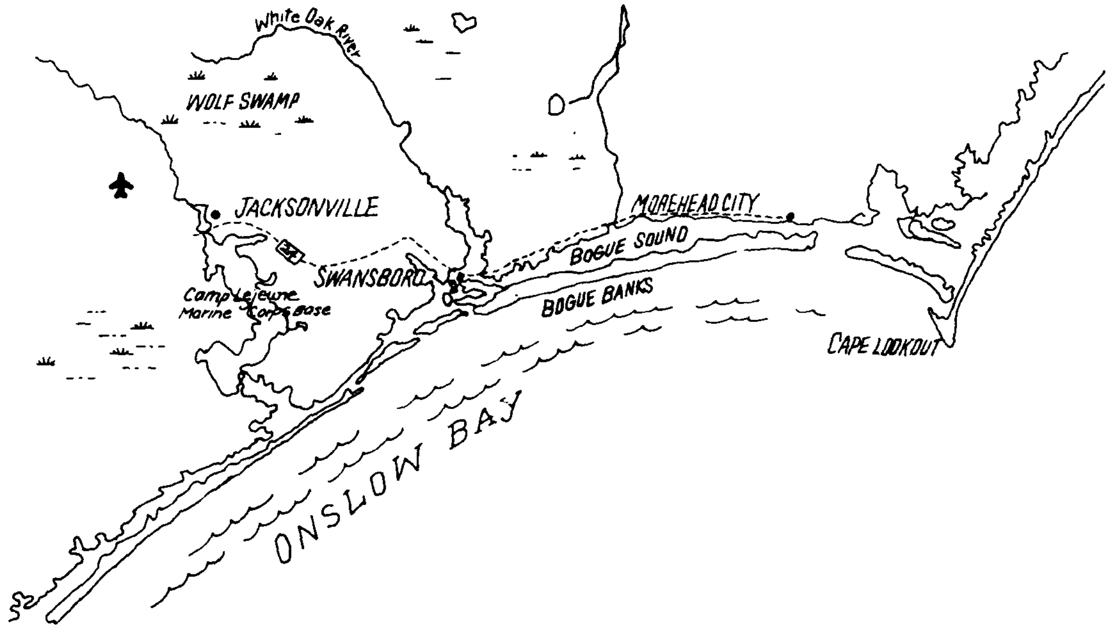

Figure 13. White Oak River estuary and surrounding area, North Carolina.

Figure 14. Georgetown, near Winyah Bay, North Carolina.

Figure 15. Winyah Bay.

identify areas of agreement and disagreement, and to move toward consensus on a course of action.

Winyah Bay, South Carolina, is a project in which the Conservation Foundation has recently been engaged. Winyah Bay supports Georgetown, which is a small maritime community of about 40,000 people, shown in Figure 14. Winyah Bay has been subject to shoaling problems as long as records have been kept.

The watershed of Winyah Bay was one of the very first areas where tobacco and rice were planted. It also has the distinction of being one of the largest watersheds in the United States, draining about 18,000 square miles.

Here again, it is appropriate to look beyond the port itself and consider what the causes are of the shoaling. In this case, the widespread agricultural use of the watershed is the predominant cause of shoaling, yet very little was done in either the distant or recent past to correct the attendant problems. Shoaling in many parts of the estuary is apparent in Figure 15, and can be seen in maps made long before any kind of human intervention.

In 1896, the first steam dredging took place, and at this time, the area was shifting from the rice plantations that had been important during the period of slavery to other uses.

In 1926, a federal channel was dredged through the lower reaches, but the upper area, as indicated in Figure 16, was still unchanged. In 1928, finally, a channel was dredged, about 18 miles in length. Several industrial proposals have been made for the Georgetown area. The earliest called for an enormous dredging project, turning basins and full port facilities.

That concept gradually evolved into the suggestion that Georgetown would be more appropriate for industrial growth. Recently, there has been still another proposal for the area known as the Estherville Plantation (Figure 17). In the 1930s, the dominant industry was paper companies. In 1970, Georgetown Steel was brought in, and this initiated more ambitious industrialization.

The U.S. Army Corps of Engineers is considering proposals for this area now. One is to maintain the existing channel to Georgetown, which was indicated in the earlier photographs, at its 27-foot depth. Another is to dredge a deeper channel, 35 feet deep, that would reguire dredging to 47 feet, and allowing it to shoal in because of the rapid rates of shoaling. This last proposal would require an enormous amount of dredge-spoil disposal. Maintaining the original 27-foot channel requires dredging 2 million cubic yards a year. Dredging a new 35-foot channel would require disposing of 22 million cubic yards of dredge spoil.

Figure 18 indicates some of the potential dredge-spoil disposal sites. It is important to note that much of this estuary is bounded by marshes and wetlands. After this vast area is allocated for dredge-spoil disposal--and keep in mind we are talking about an 18-mile channel--many uses that would have been possible for this land will disappear.

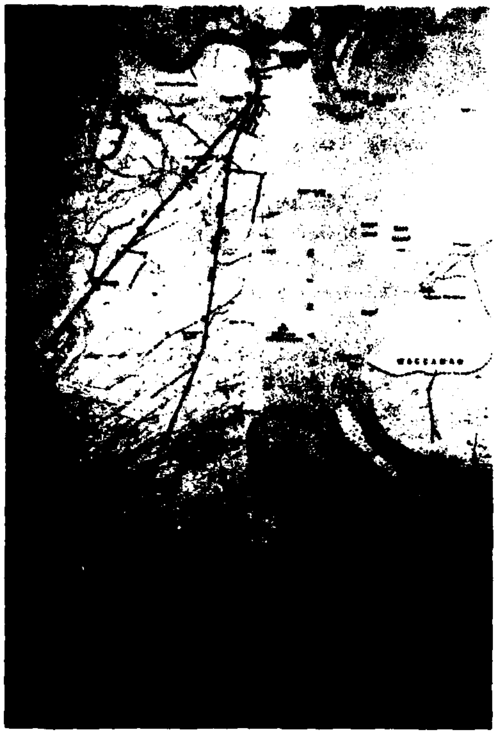

Figure 16. Upper area of Winyah Bay.

Figure 17. Estherville Plantation.

Figure 18. One proposal would deepen channels from 27' to 35'.

Figure 19. Yawkey Wildlife Center.

A new proposal that has been put together by the Carolina Refining and Distributing Company calls for the creation of a 30,000 barrel per day refinery in the vicinity of the Sampit River near Georgetown. The greatest threat that people perceive from the oil refinery is an oil spill. The vicinity of Estherville Plantation has seven rare, endangered, or threatened species, and includes eagle-nesting areas as well as habitats of red-cockaded woodpeckers, loggerhead turtles, alligators, and peregrine falcons. This has been a very significant source of concern.

The Yawkey Wildlife Center manages approximately 3000 acres of land impounded for the propagation of waterfowl in this area (Figure 19). The Corps of Engineers has taken a close look at all proposals, and has tried to work with national environmental groups to bring comprehensive planning to bear on the decisions to be made for Winyah Bay.

Summary

Many primary and secondary environmental effects are associated with port construction. Environmentalists, conservationists, or resource management agencies may raise some of these. There are as well the concerns of citizens who must live with the environmental and other consequences. These are factors to be considered with others in the design of entrances to ports and harbors. These groups should be considered in the exchange of information that informs decision making, and to that end, I would urge that you consider making a summary of your reports and other publications available to organizations such as local planning agencies and citizens' groups. Additional efforts should be undertaken to enable all interested parties to make their knowledge and views known in an open and accessible process for port planning. This will not only enable interested groups to share the knowledge and views of others, but also enable the planning of ports and harbors to be better integrated with other aspects of coastal zone management and the management of natural resources.

DISCUSSION

MAGOON: You addressed primarily marsh developments that are internal to the coast. Have you thought about, say, the effects of harbors that might be built on islands offshore?

MC CREARY: If we are talking about the Gulf Coast or the Atlantic Coast, we may well be talking about barrier islands. The Conservation Foundation has been involved in a number of studies and programs to manage barrier islands, and actually, to suggest better strategies.

SAVILLE: I wonder if you weren't talking about the possibility of artificial islands constructed offshore?

MAGOON: Really, I was just thinking that in your array of considerations, obviously one type of concept would be building port facilities offshore, rather than in or near wetlands. That would be an alternative that could be looked at. Obviously, as the dredging costs go up, perhaps it would become more attractive to go out offshore somewhat, and this could be one of the alternatives.

MC CREARY: I think that could be a very appropriate suggestion. We have not considered it, mainly because we typically get involved where there is a real controversy or a real cause, and we have not been confronted with this sort of proposal. I think it would be very interesting to do that.

BERTSCHE: A lot of these projects you get into come as a result of, say, local plans or the proposals of manufacturing interests, and yet on a national scale, clearly some of these things need to be done some place but not in my back yard. Is there a national direction on certain issues? For example, we may have to accept the loss of some marshes, some lands, in order to achieve a certain order of trade. Are we strictly limited to brush fires locally, or is there some national coordination of some of these decisions?

MC CREARY: Most of our work does happen to be in the local case study area, but we always take the study or the project with the idea in mind that we are creating some sort of a model for a broader approach that can inform other areas and national policy. One of our biggest complaints is that we have a Coastal Zone Management Act that was enacted in 1972, yet it really does not deal very comprehensively at all with estuaries and wetlands. It ignores their watersheds which, as I have indicated, are a very real problem. To my mind, the best approach I have seen so far is that of the State of California, which has in its Coastal Act a series of guidelines for constructing ports and harbors in wetlands. It addresses the idea of creating ports and harbors in degraded wetlands rather than in those that are productive.

The act also speaks to the idea of restoration or compensation. In fact, there is an agency in California, the California Coastal Conservancy, that seeks to restore, and often would seek to restore an area such as Ballona, next to an area that has been committed to marina development.

Finally, the California program has recently come up with a set of wetland guidelines which I think are the best in the country right now and guide the construction of harbors, among many other projects.

BERTSCHE: That may be a singular example, since the state owns three-quarters of the coast, and can readily set policies for its use. The problem on the East Coast is that many states, each state would have to have this individual --

MC CREARY: I think perhaps you are right, a regional perspective is warranted. Certainly each state has chosen a different approach to coastal zone management. Many of the southern states have not chosen to participate in federal programs at all. Others are much more limited in scope, compared to California, and lack the public support.

WEBSTER: Do you ever get involved with the business of proposing sites? It always seems to me that you have difficulty in this process of selecting.

MC CREARY: Many state agencies try to do industrial siting on a state or regional level, and the same approach might be appropriate for harbor and port siting. The approach is usually to go through an analysis of constraints and then select from among the areas that pass through all the screens.

In our work, again, typically we are limited to alternatives within the scope of the project. In the case of Winyah Bay, I believe one of our recommendations is among the alternatives the Corps is now pondering, for a channel enlargement. I also believe that our recommendations might address alternative industries besides the refinery to bring jobs and economic growth to the Georgetown area.

WORKSHOPS

THE WORKSHOPS

Eugene H. Harlow and John B. Herbich

The purpose of this meeting was to gain a clearer picture of the principal factors affecting the design of entrances to ports and harbors, and their interaction. To further this purpose, the workshops were structured by the panel to elicit as much of the experience, training, and informed opinion represented by the assembled participants as possible in identifying outstanding problems requiring solution. From a full list of these problems, the consensus of the group would be sought on the ten most important, and their order of significance or urgency.

Nominal Groups

The structure selected by the panel for the workshops was that of nominal groups.[1] In nominal groups, the members work in one another's presence, but without interaction. It has been demonstrated that in the critical phase of program planning reserved for speculative consideration of all aspects of a problem, or of the range of alternative directions and objectives a program might follow, interacting groups tend to generate and pursue far fewer ideas than nominal groups.[2] The nominal group technique allows a period for the silent generation of ideas. Each member then presents an idea in turn, continuing until all ideas are recorded or the alloted time expires. The ideas are not discussed: questions may be asked for clarification of statements.

First Workshop

Participants were divided by expertise and interest into three nominal groups to develop statements of the problems faced in the design of entrances to ports and harbors in the areas of: nature and the environment, the concerns of ship owners and operators, and design and maintenance. Their statements were recorded and numbered on large sheets that were then brought to plenary session. (These statements are listed in Appendix A.)

Second Workshop

The participants were assembled to read all the statements, and each was asked to list his ten selections, in order of the ten most important problems. To avoid spreading the votes too thinly, essentially similar statements were combined for a single vote. (These omnibus statements are also listed in Appendix A.) The votes were tallied, and the statements were announced. Owing to a tie vote, eleven statements were selected.

Each statement was given to a small working group for a title, final articulation, and the statement of preliminary objectives for research and other actions addressing the problems identified. These were reviewed and refined by the assembled participants, and the meeting adjourned. The product of the workshops is given in the succeeding section.

The Most Urgent Problems in the Design of Entrances to Ports and Harbors

1. PREDICTION OF SHIP MOTIONS

Improved and validated models are needed for the prediction of ship motions, vertical and horizontal, in the environmental and operational situations found in harbor entrances. These models are needed in the development of channel design geometry (depth, cross-section, shape, and planform), in the assessment of operating limits and traffic capacity, and to support the training of operators (simulators). Specific areas of weakness in existing models that should be addressed by research programs are:

--Lack of data on a wide range of ship types;
--Inability to predict the effects of
    Restricted water conditions (shallow water, banks),
    Complex, three-dimensional currents,
    Waves on lateral and vertical motions in restricted waters,
    Passing ships,
    Tugs and other auxiliary devices;
--Scale effects associated with physical models.

Research Objectives

Addressing the weaknesses of existing models, as listed above in approximately their order of importance, constitutes a preliminary research program. In all cases, research efforts should be directed by a balanced program of:

--Physical model testing, both captive and free-running, to develop data bases;

--Development of analytical predictions; and
--Selected full-scale tests for validation or data generation, or both.

2. USE OF SYSTEMS ANALYSIS IN THE DESIGN OF HARBOR ENTRANCES

The design, construction, and operation of harbor entrances involve the interaction of various government and non-government entities--ship operators and owners, the U. S. Army Corps of Engineers, the U. S. Coast Guard, National Ocean Survey (of the National Oceanic and Atmospheric Administration), Environmental Protection Agency, local port authorities, pilots and other state interests, local populace and governments--and interactions with other modes of transport, recreational boating, shoreside industries, and national and local economic interests. These interests are not all given adequate consideration in an integrated or systems-analytic manner in the design of harbor entrances.

Research Objectives

--Develop a detailed systems analysis procedure for use in harbor-entrance design
--Test the design procedure for one or more sample ports, and modify as necessary
--Sponsor interdisciplinary seminars to disseminate the systems-analysis approach, and to discuss major technical issues.

3. ENVIRONMENTAL DATA

There is a need for reliable, economical measurement, reduction, presentation, and storage of environmental data, including: tides, currents, waves, sediments, bathymetry, geometry, salinity, winds, fog, ice, and water samples (chemical analysis).

Research Objectives

The research program conducted to address these needs should determine what improvements are needed in:

--Accuracy,
--Automatic analysis techniques,
--Storage and retrieval techniques and procedures,
--Display, and
--Instrumentation

to meet the requirements of users. Some of the basic questions that will arise in the course of answering needs for environmental data are:

- --Length of measurement for a single run,
- --Interval between runs,
- --Spacing, and
- --Distinguishing interactions.

4. MODELS OF THE PHYSICAL ENVIRONMENT

Cost-effective models for predicting the environmental conditions affecting harbor-entrance design need to be evaluated, improved, and validated. These should provide typical and extreme values of waves, currents, winds, water levels, salinity, sedimentation, water quality, and other environmental parameters as a result of both natural conditions and changes caused by human activity. The information to be provided is critical to the rational design of safe and efficient harbor entrances; for example, the basic forcing functions for ship-motion modeling, determination of maintenance dredging requirements, and ability to evaluate alternative designs and assess environmental effects.

Research Objectives

The general needs to be addressed are those leading to improvements in the test data, numerical techniques, scaling techniques, physical processes, and forcing functions for each parameter and the interactions between parameters. Some examples of specific problems are:

- --Cost effective two- and three-dimensional mathematical models of all hydrodynamic processes,
- --Movable-bed modeling, scaling, and operational procedures,
- --Dispersive transport scaling in physical models,
- --Two- and three-dimensional models of transport, deposition and erosion of cohesive and noncohesive sediments,
- --Mathematical and physical models of water-quality parameters,
- --Two- and three-dimensional models of short waves and wave-current interaction in port entrances.

This list is neither inclusive, exhaustive, nor ordered by priority.

5. DISPOSAL AND USES OF DREDGED MATERIALS

The questions to be answered in this area include:

--Accumulation in the food chain of the toxic substances in dredged materials, and the possible effects on human health;

--Alteration of the biological-resource value of subtidal bottoms owing to dredging and disposal operations;

--Dynamics of dredged materials in open water: Where does it go after disposal? Does it stay put or move?

--Relationships between dredge-disposal islands, the alteration of traditional flow patterns, and consequential biological effects on estuarine organisms;

--Effects of deep-water disposal on benthic communities and biochemical cycles;

--Potential methods of increasing the productivity of bottoms through the controlled use of dredged materials;

--Alternative uses of dredged materials--for example, beach nourishment, and fill acquisition;

--Use of dredged materials for the development of needed habitats;

--New methods for reducing dredging costs;

--Effective dissemination of the results of the Dredged Materials Research Program carried out by the Waterways Experiment Station; and

--Processing and treatment of dredged materials for disposal.

Research Objectives

The research program addressing these questions should determine the susceptibility of various levels in the food chain to the toxicants present in some dredged materials,

and develop:

--Predictive models for the fate of various components of placed materials;

--Productive uses of dredged material for recreational islands, habitat-replacement projects, development of marshes, and nourishment of beaches; and

--Methods for reducing dredging costs.

The program should seek wider dissemination of the results of the Dredged Materials Research Program of the U. S. Army Corps of Engineers.

6. EROSION, TRANSPORTATION, AND DEPOSITION OF GRANULAR SEDIMENTS

Improved procedures are needed for the prediction of shoaling rates and patterns near harbor entrances. The methods offered to answer this need should be based on wave, wind, and current characteristics. The results should include the development and verification of appropriate field methodologies.

Research Objectives

The research program directed to these procedures and methods should seek improvements in:

- --Measurement of the quantities and characteristics of littoral materials;
- --Measurement and quantification of longshore energy--waves, currents, and winds; and
- --Understanding of the mechanics of waves and sediments, and of the interactions of waves, sediments, and structures.

A principal objective of the research program should be the improvement of predictive models.

7. ENTRANCE-CHANNEL DESIGN AND OPERATING CRITERIA

Improved criteria are required for the siting and design of harbor entrances. Such criteria must include:

- --Ship types, sizes, and traffic densities,
- --Appropriate aids to navigation, and
- --Expected operating equipment, in terms of waves, currents, winds, and tidal range.

Data for existing and projected entrance channels are insufficient to predict:

- --Waves, swells, and sea conditions,
- --Currents,
- --Tidal heights,
- --Salinity,
- --Sinkage and trim,
- --Vertical ship motions,
- --Vessel draft, and
- --Bank effects.

Research Objectives

To develop improved criteria, the following needs for research and development must be met:

--Determination of the sophistication necessary for adequate simulation of harbor-entry maneuvers to set harbor-design parameters;
--Further development and validation of mathematical models of ship-maneuvering motions for use in simulations of harbor-entrance transits. Such models must adequately account for effects on ship motions on waves, currents, wind, water-depth irregularities, and irregularities in the proximity of the banks;
--Establishment of mathematical expressions for the horizontal dimensions and siting of channels in simple harbor entrances as a function of design ship characteristics;
--For more complex harbor entrances; e.g., with shear currents,* selection of the best methods and procedures for studies directed to fixing the horizontal dimensions;
--Development of a mathematical formula to enable prediction of acceptable ship sizes and load conditions for given wind, tidal, sea/swell measurements, based on the horizontal dimensions of the entrance; and
--Similarly, development of statistical formulae to enable prediction of acceptable drafts.

8. STANDARDS OF SAFETY

There do not exist accepted standards, analytical techniques, or data for systematic evaluation of the navigability of harbor entrances.

Research Objectives

--A historical analysis should be performed to determine the safety records of each existing major port. Those with the best and worst safety records should be identified and studied further.

*A shear current varies locally; for example, sweeping across the mouth of a harbor faster than its uniform speed elsewhere. If a ship intersects a lateral shear current, the bow will feel the current most, with a tendency to turn the ship.

--A careful examination of these ports should be conducted, using modern port-design techniques, to determine the characteristics that enhance safety and those that lead to safety problems.
--Techniques for measuring these characteristics by reference to a common base need to be developed by experts in various disciplines (perhaps constituting an advisory board). A set of standards should be developed from these efforts to support adequate evaluation of the safe navigability of an arbitrarily selected port, and should be cast in a form that can be used in systems design.
--The standards should be promulgated by an independent, authoritative source.

9. MARINER NEEDS

The needs of the mariner should be defined in quantitative terms. These needs include (but are not limited to):

--Dependability and usefulness of aids to navigation,
--Accuracy and usefulness of charting services,
--Vessel-maneuvering requirements, and
--Vessel support services.

Research Objectives

The research program designed to investigate and quantify the needs of the mariner should:

--Develop and validate mathematical models of vessel-behavior characteristics and the effectiveness of aids to navigation;
--Conduct studies of the human-factors aspects of vessel control, and of the use of charts and aid; and
--Combine the results of these and other studies to develop simulator and physical models of existing and projected harbor entrances.

10. DECISION MAKING PROCESS

The decision making process for harbor entrances should be reviewed to enable evaluation of proposed improvements to harbor entrances, and if these improvements are indeed needed, to enable permits to be obtained and work initiated promptly.

Research Objectives

--Research case histories of delays in proposals for changes, or for new entrances to harbors, to assess the part played by the decision making process;
--Develop and test alternative decision making methods, including non-adversary methods; and
--Develop a plan for effectuating legislative action through more effective processes.

11. EVALUATION OF COASTAL-RESOURCE VALUES IN HARBOR SITING, AND RESTORATION OF HABITATS

Natural-resource values should be evaluated to ensure their proper consideration in siting and design of harbors: their determination, evaluation of their significance, and assessment is essential to achieving proper balance among environmental, economic, and other social values in decision making.

Research Objectives

--Determine why wetlands and coasts are productive,
--Investigate the origins and evolution of wetlands and coasts; and
--Establish the ecosystem response to natural events and human activities.

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1. Van de Ven, Andrew H., and Andre L. Delbecq, "Nominal versus Interacting Groups for Committee Decision-Making Effectiveness," Journal of the Academy of Management, 14 (June 1971).
2. ______________________, "A group process model for problem identification and program planning," Journal of Applied Behavioral Science, 7 (1971): 466-492.

APPENDIX A: STATEMENTS OF THE PARTICIPANTS--
Outstanding Problems in the Design of Entrances to Ports and Harbors

The statements following were developed during workshop sessions by the participants in the meeting recorded in these proceedings. They are presented here to indicate the broad array of specific concerns pertinent to the design of entrances to ports and harbors, and for readers to whom the statements will be of interest. As individual contributions, the statements should not be interpreted as necessarily representing policies or opinions of the participants' organizations, the Marine Board, or the National Research Council.

STATEMENTS OF THE SHIPS AND USERS GROUP

1. There are no criteria for the minimum horizontal dimensions of channels, given specific harbor factors such as:
   - ships (type, size, traffic density),
   - navigational aids/aids to navigation,
   - environmental data,
   - hydraulics,
   - and others.
2. No rational computer-aided procedure has been developed to evaluate harbor-entrance systems for given ship users.
3. No validated mathematical model exists for predicting ship motion (horizontal and vertical directions) in shallow water, waves, and currents.
4. Systems-analysis techniques (i.e., failure-mode hazards analysis or single failure-point analysis) are not used in the design of harbor entrances.
5. The difficulty of locating ships' positions and latitudinal set relative to the harbor entrance and channel under conditions of night, limited visibility, and stressful situations (such as heavy traffic, cold, and foreign crews) has not been resolved.
6. Regulations, operating limits, and navigational criteria are sometimes established arbitrarily, without a technical basis.
7. There is no integrated approach for including environmental, construction, maintenance, ship, operational, and economic concerns in the design of harbor entrances.
8. The additional requirements of warship accommodation in harbors are unknown.
9. Insufficient attention is paid in the design of harbor entrances to achieving minimum maintenance costs.
10. No catalog exists of generic ship types, including accurate, mathematically modeled hydrodynamic coefficients for predicting the navigability of harbors.
11. No national initiative or investment has been undertaken to develop existing and future harbors for the growth of international trade.
12. Insufficient information exists for predicting bottom clearance in existing harbor entrances--

Sinkage/trim
Wave spectra/swell
Vertical ship motion
Detailed currents
Actual tidal height
Knowledge of draft
Salinity.

13. Insufficient meteorological forecasts are available for ships operating in harbors.
14. The displacement of floating aids by weather, ice, and traffic should be given attention.
15. Insufficient consideration is given to placing the harbor entrance on the approach chart to provide the mariner with adequate maneuvering references.
16. No accepted standards or guidelines have been developed for validating models. What comparisons and level of agreement are appropriate?
17. No attention is paid to accommodating stricken vessels in ports or harbors.
18. No criteria have been articulated for selecting an optimum entrance as a function of ship type and speed, the environment, or entrance dimensions.
19. Insufficient information has been collected and analyzed to predict the effect on steering of:
    - Bottom and bottom irregularities due to silting
    - Complex three-dimensional currents
    - Currents in turns
    - Basic suction
    - Passing ships.
20. No analytical method exists for predicting three-dimensional currents on harbor entrance waterways.
21. Ship designs may not provide a piloting position with adequate perception for safe navigation within the harbor entrance area.
22 Better understanding needs to be gained of the scale effects of physical models (hydraulic and ship hydrodynamics, and the effects of harbor-entrance variables).
23. The specific support services that operate in harbor entrances (tugs, salvage vessels, dredging operations, vessel traffic services, anchorages) need to be given more attention.
24. There is inadequate detection and verification of the location of obstructions (wrecks and storm-induced shoaling, for example), and an insufficient program of removal.
25. Limited data are available for prediction of sand bar/shoaling migration.
26. Political barriers impede achievement of the maintenance requirements of existing ports.
27. There are navigational problems incident to the conflicting uses of harbor entrances--commercial traffic vs. fishing and pleasure craft, for example.

STATEMENTS OF THE NATURE AND ENVIRONMENT GROUP

101. Designate acceptable and economical dredge-disposal areas.
102. Address the following problems in dealing with spills of hazardous materials
    - Prevention and control
    - Minimizing environmental effects
    - Restoration.
103. Ensure that the new entrance will provide for safe navigation with respect to tides, currents, winds, waves, channel dimensions, and structure design.
104. Determine the accuracy of environmental information, such as waves, winds, tides, currents, and bottom characteristics.
105. Improve prediction of the rate of littoral drift as a function of wave energy.
106. Site harbors in a manner that protects natural-resource values of estuaries and wetlands.
107. Develop a consistent data base of waves and currents for port design.
108. Develop reliable methods for estimating shoaling rates and patterns in harbor interiors.
109. Investigate the effects of mitigation practices, and development of other habitats.
110. Minimize the costs of maintenance dredging through navigational aids, channel siting, control structures, optimum dredging and disposal operations.
111. Provide for accurate prediction of the environmental effects of dredged material placed in the water.
112. Predict siltation rate in a dredged navigation channel seaward of a harbor entrance.
113. Test and validate techniques for habitat restoration.
114. Develop cost-effective models of waves, currents, water levels, tsunamis, storm surges, sedimentation, and other hydrodynamic processes.
115. Develop reliable methods of predicting seiching in harbors.
116. Educate the public to enhance participation in planning.
117. Ensure that changes caused in the physical parameters (tides, currents, salinity, etc.) are not so drastic as to cause major adverse environmental effects.
118. Develop cost-effective technology for measurement of waves, tides, salinity, sediments, etc.
119. Experiment with new techniques for sand bypassing at harbor entrances.
120. Design efficient decision making processes that involve all parties with legitimate environmental concerns.
121. Develop real-time systems to provide data on wind, waves, and currents as aids to navigation.
122. Develop and validate field procedures to establish shoaling rates.
123. Estimate alterations in the biological resource values of bottoms.
124. Design breakwaters for deep water.
125. Solve wave-current interaction problem.

126. Improve communication of findings and implications of research to policy makers.
127. Predict the hydrodynamics of ship-ship interaction in a confined channel.
128. Develop low-energy methods for maintaining navigable channels.
129. Integrate watershed management as a consideration in port planning.
130. Develop a systems approach to integrating all aspects of the natural environment in port planning.
131. Develop techniques for predicting changes in physical and chemical parameters resulting from harbor entrance redesign.

STATEMENTS OF THE DESIGN AND MAINTENANCE GROUP

201. There is not enough basic data on existing harbor entrances with which we can model capability.
202. The needs of the mariner, as they affect harbor-entrance design, need to be defined quantitatively.
203. There is a need to develop better concepts and designs of seagoing cutter-head dredges and discharge pipelines that can operate efficiently in the open sea.
204. Cost-effective methods of quantifying physical environmental parameters in coastal areas should be sought.
205. The state of the art of design and maintenance of rubble-mound harbor entrance structures needs advancement.
206. The full impact of the design on all users of coastal zones needs to be recognized.
207. Harbor-entrance design demands systems analysis.
208. There are unmet needs for reliable quantitative hydraulic (and/or) mathematical models for the prediction of tides, currents, waves, salinity, and sediment changes in harbor entrances as a function of various design configurations.
209. A draft of a national decision making process (replacing that of the National Environmental Protection Act of 1969) that evaluates needs and desires, and avoids adversary processes needs to be submitted to Congress, so that permits are obtained and action started promptly on improvements that are required.
210. A technique should be developed to minimize the conflicts of *split governmental responsibility* to allow more effective implementation of harbor entrance projects.
211. Standards of safety need to be established to limit the risk of casualties.
212. There is a need for better estimates of shoaling rates in approach channels for different sediments and different waves and currents.
213. A cost-effective instrumentation system is needed with which to measure synoptically vessel excursion and forcing physical function in harbor entrances.
214. A users manual and associated short course(s) on the planning and design of harbor entrances should be produced.

215. A mechanism should be developed to identity the operational limitations and constraints that are implicit in basic design.
216. Improved procedures are needed to predict the capabilities of existing harbor entrances to accommodate new systems (of managing vessel-traffic flow, for example) and to identify the minimum improvements needed to accommodate these new systems, as well as constraints.
217. What is the proper design of a bridge across a harbor entrance? Can reliable energy-absorbing systems be developed to withstand ramming by a ship?
218. Research on the processing, treatment, and placement of fine dredged sediments is needed to make them suitable for upland use or deep-sea deposition.
219. With respect to harbor-entrance design, there is a need to develop a more effective technique for disseminating information about results of the U. S. Army Corps of Engineers' Dredged Materials Research Program.
220. The recent reduction in maintenance dredging and in other related harbor-entrance activities should be reversed.
221. Second- and third-generation mathematical models should be developed to predict the behavior of ships in an approach channel, between the jetties, and in the harbor. These are necessary for (among other important functions):
    - Checking the design of ship channels, and
    - Determining the geometry of the channel entrance.
222. There is a need for better quantification of physical environmental parameters in coastal areas (i.e., waves, climate, currents, sediment movement, etc.).
223. The projected marine traffic mix and density need to be better identified and incorporated into the design of harbor entrances, using improved models.
224. A model should be developed to demonstrate effectively the relationship between optimum port and channel use, and the channel-entrance design.
225. Additional financing resources for entrance improvements are needed to serve national and regional, as well as local interests.
226. Better quantification is needed of the economic benefits realized by improvement of harbor entrances.
227. The development of fixed systems to permit sand bypassing of the harbor entrance should be continued.
228. The feasibility of open-water disposal of dredged materials should be re-evaluated.

OMNIBUS STATEMENTS (combined for a single vote by unanimous consent)

105, 108, 122, 212, 25, 112	Need for better estimates of shoaling rates
101, 111, 228, 218, 219	Research on dredged materials to improve disposal
124, 205	Design of breakwaters, improvement of rubble-mound structures

3, 221, 19, 127	Need for improved second- and third-generation mathematical models--ship motion in shallow water, ship-ship interaction, etc.--to determine geometry and check the design of harbor entrances
106, 109, 113	Research, evaluation, and methods for preservation of valuable natural resources, and the restoration of habitats
4, 7, 207, 130	Need for systems analysis and integrated approach to the design of harbor entrances
20, 114, 131, 208	Cost-effective models of hydrodynamic processes--waves, currents, water levels, sedimentation, and others
1, 18, 12	Criteria for minimum horizontal dimensions of channels
211, 103	Need for standards of safety
202, 14, 23, 15	Quantitative definition of the needs of mariners
119, 227	Development of sand-bypassing systems
222, 201, 104, 107	Better quantification of physical environmental parameters
118, 204	Cost-effective technologies for the measurement, analysis, and presentation of wave, tide, and other data

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